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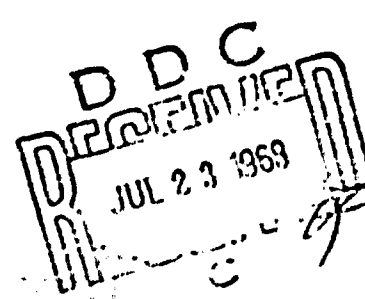


TR-20-(VOL. 1)



# SHELTER DESIGN AND ANALYSIS

VOLUME 1  
FALLOUT  
PROTECTION



OFFICE OF CIVIL DEFENSE

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### ACKNOWLEDGEMENT

The volumes from which material was compiled for this textbook include:

"The Effects of Nuclear Weapons," prepared by the Defense Atomic Support Agency of the Department of Defense under the editorship of Samuel Glasstone in coordination with other cognizant agencies and published by the Atomic Energy Commission: "Fallout Shelter Surveys-Guide for Architects and Engineers" and "Design and Review of Structures for Protection from Fallout Gamma Radiation." The latter two are Office of Civil Defense publications based on the National Bureau of Standards Monograph 42 "Structure Shielding against Fallout Radiation from Nuclear Weapons" by Dr. Lewis V. Spencer. To these have been added a number of Army and Navy booklets on related subjects.

At the request of the Architectural and Engineering Development Division of the Office of Civil Defense, this volume has been compiled by the staff of the Protective Construction Section of the U. S. Army Engineer School, Fort Belvoir, Virginia. Many professors and instructors from various schools and universities who presented courses in Fallout Shelter Analysis also contributed to the preparation of this textbook by reviewing the draft manuscript and offering helpful suggestions. Their cooperation is acknowledged with gratitude.

## FALLOUT PROTECTION

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## INTRODUCTION

This textbook combines in one volume, for the first time, most of the material covered in the Fallout Shelter Analysis courses for architects and engineers sponsored by the Office of Civil Defense. It is intended for use by practicing professionals enrolled as students in formal graduate level university courses under the direction of professors well versed in the methods and techniques of shelter design and properties and effects of fallout gamma radiation. This volume confines itself to design and analysis of structures for protection against radioactive fallout, which presents the most widespread threat to our population in the event of a thermonuclear attack. The feasibility of incorporating inherent fallout protection into the design of many buildings and structures at little cost will be apparent when the designer becomes aware of the problem and familiar with the principles of fallout shelter design and analysis.

The text is not intended to be used as the source of detailed background information on nuclear physics or weapons effects. The most up-to-date and comprehensive volume available to the public on this subject is **THE EFFECTS OF NUCLEAR WEAPONS (E.N.W.)** and familiarity with it is recommended in the use of this book.

Special two-week intensive graduate level short courses are currently available at a number of major universities and military engineering schools throughout the country. Night, Saturday, and correspondence courses have been initiated for those who cannot attend full time short courses. Information on the locations and schedules for Fallout Shelter Analysis Courses may be obtained from the nearest Regional Office of the Office of Civil Defense.

While the methods and techniques developed herein are based on the analysis of weapons tests and upon research and studies by nuclear scientists and engineers, every effort has been made to present the material in a form readily understood by the practicing architect or engineer. The systems of analysis are not difficult, but they do become complicated for complex structures. It is, therefore, strongly recommended that the reader develop his ability to apply these methods by pursuing one of the formal courses of study mentioned above before undertaking the design or analysis of fallout shelters.



## CHAPTER 1

### BASIC NUCLEAR PHYSICS AND NUCLEAR WEAPONS EFFECTS

#### 1.1 INTRODUCTION

It is not necessary to be a nuclear physicist to analyze or design structures for fallout protection. However, a basic knowledge of the concepts and terminology associated with the structure of matter, radioactivity, fission and fusion, weapons effects, and attenuation of radiation are essential to understanding of need for fallout protection and the background of the system of analysis. The information provided in this chapter is a general survey and is intended to be supplemented by readings in DAP 39-3, THE EFFECTS OF NUCLEAR WEAPONS.

#### 1.2 STRUCTURE OF MATTER

##### 1.2.1 ELEMENTS AND COMPOUNDS

All matter is made up of elements and compounds. Compounds consist of two or more elements and may be broken down into simpler substances or formed from simpler compounds or elements by chemical reaction. The components do not exhibit the characteristics of the original compound. For example, sugar is a compound which can be broken down into the elements carbon, hydrogen, and oxygen. The smallest subdivision of the compound which still retains its properties is the molecule, which is a group of two or more atoms tightly held together.

The distinction between an element and a compound is made on the basis of chemical reactions. Chemical reactions may be produced by heating, applying pressure, using a substance which promotes reaction (catalyst), electrolysis, and so forth. If large numbers of reproducible experiments on a pure isolated substance show that none of these means is capable of breaking that substance down into still other substances, then that substance is said to be an element. There are 92 naturally occurring elements. Ten more have been produced artificially by man in laboratories. From these 102 elements, it is possible to produce by chemical reaction all the compounds known (as well as many as yet unknown). For example, water is built up from the elements hydrogen and oxygen; when two atoms of hydrogen combine with one atom of oxygen, they form one molecule of the compound water.

It is exceedingly difficult to visualize the fantastically small size of atoms. For example, in one grain of ordinary table salt, there are approximately 1,300,000,000,000,000,000,000 ( $1.3 \times 10^{21}$ ) atoms, half of which are sodium atoms and half of which are chlorine atoms. Each atom has a diameter of about 0.00000001 centimeter.

Each element has a different name and is represented by a symbol, which is simply a shorthand notation. For example, the element hydrogen is given the symbol "H"; the symbol for the element helium is "He". In general, these symbols are chosen as the first one or two letters. It is necessary to use other letters for some elements. Also, some of the symbols appear illogical as they are based on the old Latin names for the elements, such as "Na" for sodium and "Au" for gold. The great advantage of the element symbols is that they enable one to represent chemical reactions and chemical compounds in an abbreviated fashion. A molecule of water composed of two atoms of hydrogen and one atom of oxygen can be represented by the notation "H<sub>2</sub>O".

#### 1.2.2 ATOMIC STRUCTURE

Despite their extremely small size, atoms are composed of still smaller particles. There are basically 3 such particles, the electron, the proton, and the neutron. The many different kinds of atoms are essentially formed from these three particles, present in different numbers.

Although atoms of one element differ from those of another, all atoms have the same general type of structure and are often described by comparing them to our solar system. The nucleus is the center of the atom, just as the sun is the center of our solar system. The nucleus has a positive electrical charge and is composed of one or more protons and neutrons. Moving at great speed around the nucleus in orbits, much as planets move about the sun, are a number of particles called electrons. The electrons have a negative charge. This structure is indicated in Figure 1.1. It should be noted that the atom contains an equal number of electrons and protons. This conception or "model" of the atom has been replaced by more sophisticated conceptions based upon wave mechanics and probability. This model is adequate however, to explain the nuclear phenomena of interest in shelter analysis.

The nucleus contains almost all of the mass of the atom, yet the diameter of the atom is roughly 10,000 times the diameter of the nucleus. The atom, therefore, is mostly space. Each of three basic particles comprising an atom has a specific charge and mass.

"Charge" refers to their electrical charge and although "mass" has a precise meaning in physics, for the purposes of this text, it may be considered synonymous with "weight" without a serious error in reasoning. For simplicity in dealing with atomic phenomena, the magnitude of the electric charge on an electron has been chosen as one unit of charge. Since atoms are so small, it is inconvenient to use pounds, ounces, or even grams to measure their mass. The mass is measured by the atomic mass unit (amu) system. On the scale of this system, the mass of the proton is approximately one mass unit, and the other particles may be compared with it as a standard. The amu is defined precisely as one-sixteenth the mass of the neutral oxygen sixteen atom and is equal to  $1.66 \times 10^{-24}$  grams.

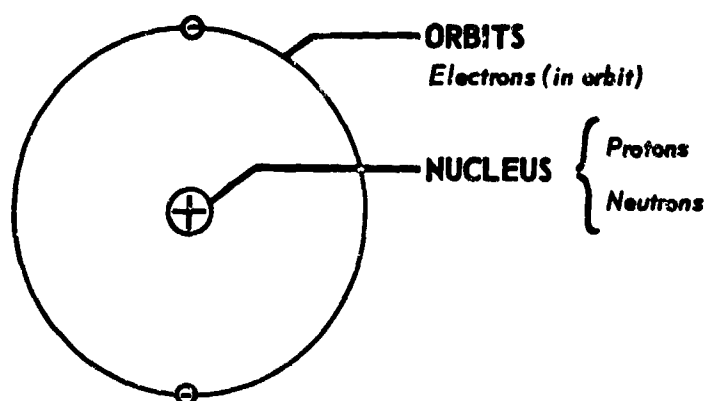


Figure 1.1 Structure of an atom.

### 1.2.3 PARTICLES OF AN ATOM

**Electron** - The electron is a negatively charged particle and has a mass of approximately  $1/1845$  amu. It is by far the lightest of the three basic particles. By convention, the charge of the electron is negative (-) and is one electronic charge in magnitude. The electronic charge, so defined, is equal to  $4.8 \times 10^{-10}$  electrostatic units and is the smallest discrete charge observed in nature.

**Proton** - The proton has a mass of approximately 1 atomic mass unit and has a charge of +1.

**Neutron** - The neutron has a mass only slightly larger than that of a proton; it may be taken as having a mass of 1 mass unit for the purposes of this text (its mass may be stated as 1+ to indicate that it is slightly more than that of the proton). The

neutron has no electric charge. As the nucleus of an atom contains protons and neutrons, it has a positive electrical charge and the magnitude of this charge is the same as the number of protons. The properties of these particles are summarized in Table 1.1.

Table 1.1 Properties of Atomic Particles

PARTICLE	CHARGE	MASS (amu)		LOCATION WITHIN THE ATOM
		Exact	Approximate	
Electron	-1	0.00055	$\frac{1}{1845}$	Outside the nucleus
Proton	+1	1.00758	1	In the nucleus
Neutron	0	1.00894	1+	In the nucleus

Figure 1.2 shows some examples of atomic structures to illustrate that the atoms of all elements are built up from different combinations of the same three basic particles.

#### 1.2.4 THE A AND Z NUMBER SYSTEM

A shorthand notation has been developed which quickly indicates the exact structure of any atom. The notation is as follows:

$${}_Z^AX, \text{ in which}$$

X - is a general representation of any element symbol (in each case the appropriate element symbol would be used)

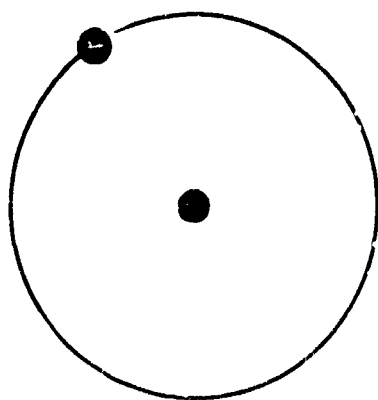
Z - the number of protons in the nucleus.

A - the number of protons + neutrons in the nucleus.

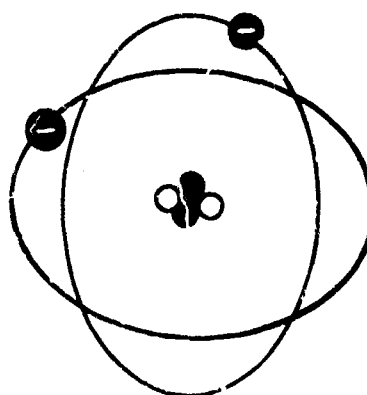
The Z number is usually called the atomic number. Since the Z number is equal to the number of protons in the nucleus, it is also equal to the number of electrons outside the nucleus in the normal neutral atom. Therefore, each element will have its characteristic Z number. For example, the element sodium will always have a Z number of 11, and conversely, a Z number of 11 will always identify the element sodium.

Although chemical properties of an atom depend directly on the number of electrons it possesses, it is possible to say that

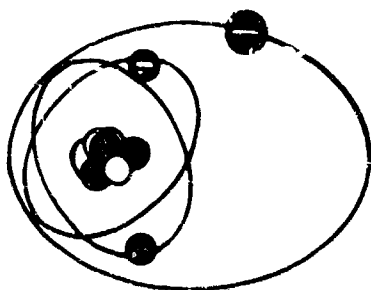
NOTE: The representation of electronic orbits as elliptical is more accurate than representation as circles; however, for simplicity they will be represented as circles elsewhere in this text.



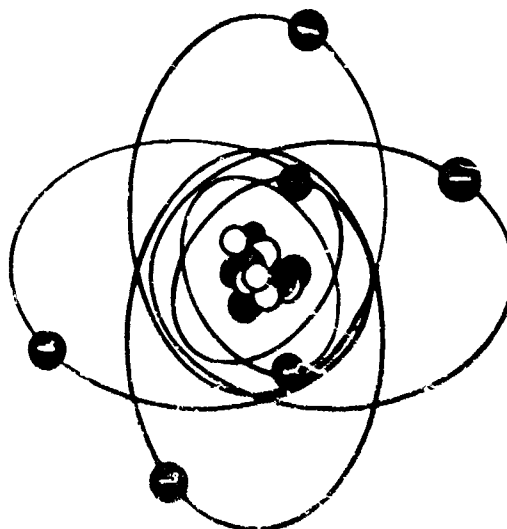
HYDROGEN  ${}_1\text{H}^1$



HELIUM  ${}_2\text{He}^4$



LITHIUM  ${}_3\text{Li}^7$



CARBON  ${}_6\text{C}^{12}$




-  Electron
-  Proton
-  Neutron

Figure 1.2 Examples of Atomic Structure

the chemical properties depend on the number of protons because there are an equal number of protons and electrons in a neutral atom.

The A number is often called the nucleon number. A nucleon is defined as any particle found in the nucleus; the term simply provides a convenient way of referring to both protons and neutrons. Since the A number represents the sum of the protons and neutrons, it is equal to the number of nucleons. The A number is also called the mass number. As the mass of both the proton and the neutron is approximately one, the sum of protons and neutrons gives the mass of the nucleus (and of the atom, since the masses of the electrons are nearly zero).

The number of neutrons in the atom can be determined by finding the difference between the A and Z numbers.

$$A - Z = \text{number of neutrons.}$$

An example of the A and Z number terminology and the deductions that can be made from it are indicated below.

Example:  ${}_{17}\text{Cl}^{35}$

Number of protons in this atom: 17

Number of electrons in this atom: 17

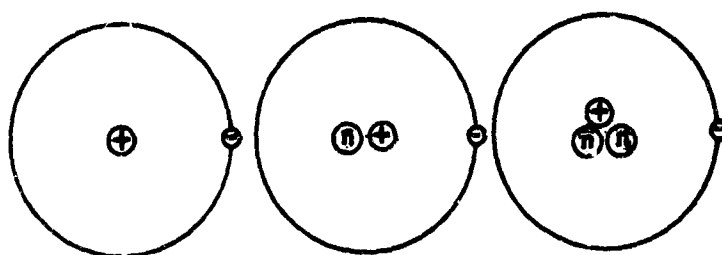
Number of neutrons + protons in this atom: 35

Number of neutrons in this atom:  $35 - 17 = 18$

Element of which this is an atom: Cl (chlorine).

#### 1.2.5 ISOTOPES AND NUCLIDES

It is possible for different atoms of the same element to have somewhat different nuclear structures. This difference is not in the number of protons, since the element is determined by the number of protons in the nuclei of the atoms of that element. The difference is in the number of neutrons. For example, there are three known forms (isotopes) of the element hydrogen, two of which are found in nature and one of which is man-made. The structures of these three atomic forms of hydrogen are shown in Figure 1.3.



Number of protons	1	1	1
Element	Hydrogen	Hydrogen	Hydrogen
Element symbol	H	H	H
Number of neutrons	0	1	2
Number of nucleons	1	2	3
Complete symbol	${}_1\text{H}^1$	${}_1\text{H}^2$	${}_1\text{H}^3$

Figure 1.3 The isotopes of hydrogen

Since two different atomic forms of an element (isotopes) have the same number of protons, they have the same number of electrons and therefore they will have the same chemical behavior. Differences do occur in physical properties however, for example, hydrogen 1 ( ${}_1\text{H}^1$ ) and hydrogen 2 ( ${}_1\text{H}^2$ ) are not radioactive, but hydrogen 3 ( ${}_1\text{H}^3$ ) is radioactive.

The three isotopes of hydrogen have become very important in nuclear work. As a result, each has been given a separate name for ease in identification. These names are:

Hydrogen 1	(common) hydrogen
Hydrogen 2	deuterium
Hydrogen 3	tritium

Hydrogen is the only element for which a special nomenclature has been devised for the different isotopes. For all other elements, the different isotopes are spoken of by the more basic nomenclature; for example,  ${}_2\text{He}^3$  and  ${}_2\text{He}^4$  are referred to as helium 3 and helium 4, respectively.

The term "isotope" is only used for elements which have more than one atomic form, and when distinguishing the different forms of

the same element. Thus, helium 3 and helium 4 may be referred to as the isotopes of helium.

The term "nuclide" should be used when referring to specific forms of different elements. Thus, a statement would read, "Two radioactive nuclides commonly used to calibrate radioactive instruments are cobalt -60 and cesium -137" and not, "Two radioactive isotopes, etc." This usage of the terms "isotope" and "nuclide" will be followed in the text.

Since all nuclides are composed of varying numbers of neutrons and protons, they can all be represented by the A and Z number notation. Only certain combinations are possible, some of which are observed to be stable and some of which are unstable. Generally, the lightest elements are stable when the numbers of protons and neutrons are approximately equal, or in a 1 to 1 ratio. As the elements become heavier, more neutrons than protons are found in the stable combinations so that among the heaviest elements, a ratio of  $1\frac{1}{2}$  neutrons to 1 proton is found.

### 1.3 RADIOACTIVITY

#### 1.3.1 HISTORICAL BACKGROUND

Nuclear radiation was discovered in 1896 by a French scientist named Henri Becquerel. Becquerel experimented with fluorescent crystals which when struck by ordinary white light gave off light of some other color, such as pink or green. He thought that he had discovered that certain crystals, when struck by light gave off some sort of very penetrating rays different from light rays which could penetrate thin sheets of paper or metal.

Becquerel repeatedly performed the following experiment to determine the properties of the substances that gave off the penetrating rays:

He wrapped a piece of paper about a photographic plate so that light could not reach the plate and expose it; then, on top of the paper, he put a small pile of crystals of a salt of uranium. He then placed this apparatus outdoors in the sun all day. At the end of the day, he brought the entire set of materials indoors and developed the photographic plate. He always found a black spot on the plate under the crystals. This led him to the belief that when these crystals were exposed to light they gave off some previously unknown kind of radiation which was capable of penetrating the paper and exposing the film.



Becquerel's experiments with these crystals might have provided no more information than this had not it been for a lucky accident. One day when preparing to set his standard experiment in the sun, the sun failed to come out; he therefore placed the entire apparatus in his top desk drawer to await a sunny day. As it happened the sun failed to shine for several days; on the first day that it did come out he was going to place the apparatus in the sun, but, for some unknown reason, he developed the plate directly instead. The plate was blackened under the crystals. Becquerel then revised his original conclusion about these crystals. The penetrating rays were given off spontaneously from within the material itself without the assistance of any outside agency such as sunlight. It is now known that these radiations come from the nuclei of the atoms of the material; for this reason, they are called nuclear radiations.

Further research by Becquerel and others demonstrated that the emission of the strange new penetrating rays by these substances (called radioactive substances) was unaffected in any manner by heat, light, pressure, chemicals, mechanical force, or any other means then known. Much experimental work was done in the years following Becquerel's discovery in an attempt to understand these rays.

### 1.3.2 TYPES OF RADIATION

It was believed initially that only one kind of ray was emitted by radioactive substances. The nature of this ray was unknown. In the experiment depicted in Figure 1.4 (a), a sample of radium (one of the few radioactive substances known at the time) was placed at the base of a cylindrical hole drilled in a piece of lead (the figure shows a cross section of the lead block). Since lead has the ability to absorb radiation very effectively, little of the radiation penetrated through the sides of the block. Therefore, there was essentially a straight beam of radiation coming out of the hole. A photographic plate was placed across the path of the radiation and upon development showed one dark spot in the center of the plate.

In a later experiment depicted in Figure 1.4 (b), the beam of radiation was subjected to a strong electrical field. This time there were three black spots on the plate, indicating that the electric field had separated the beam of radiation into three kinds of radiations, as illustrated in the figure. The three types of radiation were arbitrarily identified by the first three letters of the Greek alphabet--

alpha ( $\alpha$ ) for the radiation attracted to the negative side of the field,

beta ( $\beta$ ) for the radiation attracted to the positive side of the field, and

gamma ( $\gamma$ ) for the radiation not attracted to either side.

Similar experiments using magnetic fields also produced a separation of the beam of radiation into three components.

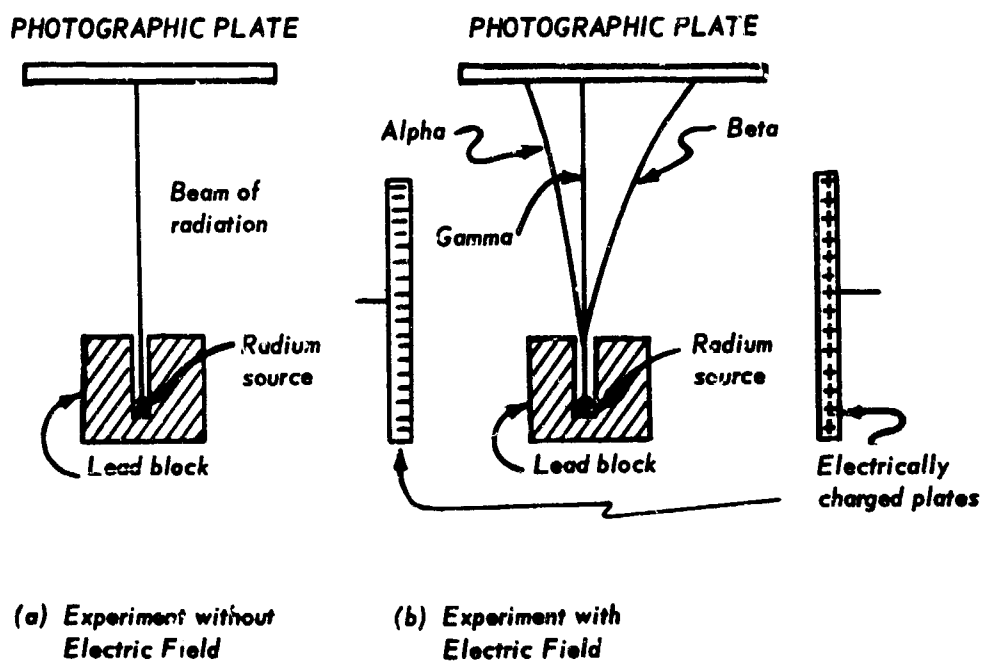


Figure 1.4 Path of emanations from a radium source; (a) without electric field; (b) with electric field.

Several conclusions can be reached as a result of the illustrated experiment beyond the isolation of three kinds of radiation. The experiment indicates that: (1) alpha radiation, which was attracted to the negative plate, has a positive electric charge; (2) beta radiation has a negative charge; and (3) gamma radiation, which was undeflected by the electric field, has no charge (is electrically neutral).

### 1.3.3 PROPERTIES OF NUCLEAR RADIATIONS

#### 1.3.3.1 General Properties

Alpha. Alpha radiation consists of high velocity particles, each with a charge of +2. Each particle has a mass of 4 atomic mass units and thus each particle is the same as the nucleus of the helium -4 ( ${}^4\text{He}$ ) atom. The helium -4 atom has two protons and two neutrons in the nucleus and two electrons outside the nucleus to balance the charge. If the electrons were stripped away, the resulting nucleus would be identical with an alpha particle. The configuration of two protons and two neutrons is an extremely stable nuclear structure. This helps explain why this structure is emitted from a nucleus in preference to other combinations of nucleons.

Beta. The experiment on the separation of radiations showed that beta radiation has a negative electrical charge. Beta radiation is a stream of electrons traveling at high speed. The mass of a beta particle is  $1/1845$  atomic mass unit and its charge is -1. It is identical with electrons which orbit about the nucleus of atoms except for its speed and origin. Note that beta particles originate in the nucleus of the atom.

Gamma. Gamma radiation has no electrical charge, and appropriate experiments have proven that it has no mass. Gamma radiation is pure energy traveling through space at the speed of light. It is one example of a general type of radiation termed electromagnetic radiation, which include radio waves, light waves, and X-rays. The type of radiation most similar to gamma radiation is X-rays, which has about the same or somewhat less energy as gamma radiation. The distinction between them is their origin.

X-rays originate in the region of the orbital atomic electrons whereas gamma rays come from within the nucleus.

#### 1.3.3.2 Specific Characteristics of Electromagnetic Radiations

Electromagnetic radiations are identified by their characteristic wave length ( $\lambda$ ) and frequency ( $\nu$ ) and their energy (E). These properties are related by two simple formulae:

$$c = \lambda \nu$$

where  $c$  = the speed of light,  $3 \times 10^{10}$  cm/sec  
 $\lambda$  = wave length, normally measured in centimeters  
 $\nu$  = frequency, normally measured in reciprocal seconds ( $\text{sec}^{-1}$ ).

Since  $c$  is a constant, frequency increases as wave length becomes shorter.

$$E = h \nu$$

where  $E$  = energy of one photon or quanta of radiation (ev)

$h$  = Plank's constant, equal to  $6.625 \times 10^{-27}$  erg-sec.

$\nu$  = frequency (sec<sup>-1</sup>)

Since  $h$  is a constant, it is evident that the higher the frequency, the greater the energy of the radiation.

Energy of radiation is normally expressed in units of electron volts (e.v.) or million electron volts (MEV). An electron volt is the amount of energy acquired by one electron moving through a potential difference of one volt. One e.v. is equal to  $1.602 \times 10^{-12}$  ergs. The unit of MEV is convenient for the kinetic energy of alpha and beta particles as these particles usually have energies in the millions of electron volts.

Table 1.2 summarizes the properties of the three types of radiation.

Table 1.2 Properties of Nuclear Radiations

TYPE OF RADIATION	SYMBOL	CHARGE	MASS (amu)	CHARACTER- ISTIC	EFFECT OF EMISSION ON PARENT NUCLEUS	
					Atomic No.	Mass No.
Alpha particle	$2\alpha^4$ , or $2\text{He}^4$	+2	4	2 Protons 2 Neutrons (same as nucleus of He-4 atom)	Decreases 2	Decreases 4
Beta particle	$-1\beta^0$ , or $-1e^0$	-1	$\frac{1}{1845}$	High speed electron	Increases 1	No change
Gamma ray	$0\gamma^0$	0	0	Form of electro- magnetic energy similar to X rays	No change	No change

### 1.3.4 RADIOACTIVE DECAY

#### 1.3.4.1 Definition

Certain nuclear structures have excess energy and are thus unstable. Such atoms attempt to reduce their energy content by releasing energy. They do this, in the case of most nuclei, by emitting one of the three types of radiation; alpha, beta, or gamma.

In definition, radioactive decay is the spontaneous attempt of an unstable nucleus to become stable, usually by the emission of particles or rays.

#### 1.3.4.2 Nuclear Forces

It may appear peculiar that the nucleus is held together at all. Since like charges repel, the electrical (coulomb) forces between protons apparently should cause the nucleus to fly apart. However, the repulsive coulomb forces between protons are overcome by other forces within the nucleus. These forces are of very short range and only act between nucleons close to each other. A balance occurs between the attracting nuclear forces and the repelling coulomb forces and as a result, the nucleus stays together. In unstable atoms, this balance is a delicate one. If the repelling coulomb forces should overcome the attracting nuclear forces, part of the nucleus may break off and escape. In other cases, rearrangements within the nucleus which lead to more stable configurations may take place without the loss of particles. Nuclides whose nuclei undergo this process are said to be unstable or radioactive.

#### 1.3.4.3 Modes of Decay

Alpha Decay. The configuration of the helium nucleus is extremely stable, which leads to its ejection from a nucleus as a unit. The off-going alpha particle has considerable kinetic energy. The energy of the nucleus which emits the alpha particle is decreased by the amount of the kinetic energy imparted to the particle.

Beta Decay. It is not so easy to visualize how a beta particle can be emitted from a nucleus. The statement that beta radiation comes from the nucleus, but that there are no electrons in the nucleus appears to be a contradiction. The accepted explanation for this result is that it is possible for a neutron to split into a proton and an electron. If this splitting occurs, the electron is then ejected from the nucleus with great speed (great kinetic energy), with a corresponding reduction of energy of the nucleus.

Gamma Decay. Nuclei may release gamma radiation as a means of decreasing their energy content. Since gamma radiation consists of pure energy, its emission reduces the energy of the nucleus by the energy magnitude of the emitted  $\gamma$ -ray. This emission of gamma radiation accompanies a rearrangement of nuclear particles; it does not involve a change in the number or kind of nucleons in the nucleus. It often occurs concurrent with beta emission.

#### 1.3.4.4 Measurement of Activity

A particular radioactive nucleus may decay at any time, or it may never decay. When large quantities of these radioactive atoms are present, however, probability of decay can be expressed statistically in terms of the disintegrations taking place per unit time. Activity is defined as the number of atoms disintegrating per unit time. A unit of measurement of activity is the curie, which is defined as  $3.7 \times 10^{10}$  disintegrations per second. Mathematically, activity is expressed by the equation

$$A = \lambda N$$

where  $A$  = Activity, in disintegrations/sec.

$N$  = number of radioactive atoms present.

$\lambda$  = decay constant, expressed in terms of reciprocal time.

#### 1.3.4.5 Decay Formula

When the formula expressing activity is integrated as a function of time, the following relation, which can be verified experimentally, is obtained:

$$N = N_0 e^{-\lambda t}$$

where  $N$  = number of radioactive atoms, present at any time  $t$

$N_0$  = number of radioactive atoms present at  $t=0$

$\lambda$  = decay constant

$t$  = time

$e$  = the base of the natural logarithms, a constant.

Examination of this expression shows that although the number of radioactive atoms present, and thus the activity, decreases with time, it never reaches zero. This equation will plot as a

straight line on a semi-logarithmic scale.

#### 1.3.4.6 Half-life

Half-life is defined as the elapsed time required for the activity to decrease to one-half its original value. As shown by the equation  $A = \lambda N$ , the activity is directly proportional to the number of radioactive atoms present. Thus, the half-life can also be defined as the time required for the number of a particular radioactive nuclide to decrease by one-half. For example, iodine -128 has a half-life of 25 minutes. If the activity of a sample of iodine -128 is 400 disintegrations per second at a time  $t$ , then 25 minutes later, the activity of the remaining iodine -128 would be 200 disintegrations per second. Note that only half of the iodine -128 would remain at the end of the 25 minutes.

Half-lives vary for radioactive isotopes of a single element and for radioactive nuclides of different elements. Some are extremely short, such as  $10^{-4}$  seconds for astatine -215, while others are quite long, as  $7.1 \times 10^8$  years for uranium -235. The half-life of a radioactive isotope is constant and is independent of the amount of radioactive atoms present or the age of these isotopes.

#### 1.3.5 ARTIFICIALLY INDUCED NUCLEAR REACTIONS

A few radioactive nuclides are found in nature. In addition, man has learned to produce nuclear reactions artificially, thus, creating new radioactive nuclides not found in nature and producing other results which are of considerable importance. Normally, artificial reactions in atoms are induced by firing nuclear particles at a target containing that type of atoms. The nuclear particles used as projectiles are made to move at great speed (with great energy) by the use of machines called particle accelerators. The following are particles most commonly used as projectiles:

Alpha particle -  ${}_2\text{He}^4$

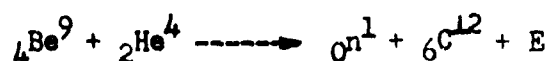
Beta particle -  ${}_1\beta^0$

Proton -  ${}_1\text{H}^1$ ; nucleus of the hydrogen -1 atom

Deuteron -  ${}_1\text{H}^2$ ; nucleus of the hydrogen -2 (deuterium) atom.

Some typical examples are given below to indicate the general nature of artificially induced nuclear reactions.

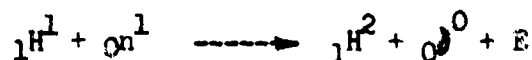
Alpha-neutron type:



Alpha-proton type:



Neutron-gamma (radiative capture) type:



It should be understood that in each of the reactions shown above, the particle or ray emitted, such as a neutron, proton, or gamma ray, is emitted almost instantaneously when the reaction takes place. For instance, in the last example above, the equation does not mean that  ${}_1\text{H}^2$  is radioactive and a gamma emitter; the gamma ray shown is emitted at the instant of the reaction. The product  ${}_1\text{H}^2$  in this case is stable. In other cases, the product may be radioactive. Thus, the product nuclei may continue to emit radiation.

#### 1.4 FISSION AND FUSION

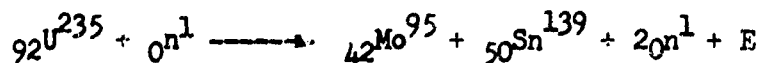
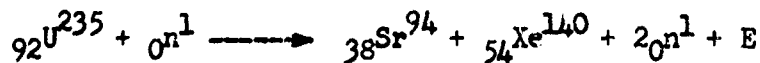
Two artificially induced nuclear reactions which are of great importance are the two used in nuclear weapons: fission and fusion.

##### 1.4.1 FISSION

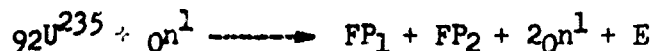
The process of fission involves the splitting of very large nuclei, such as those of uranium -235, of plutonium -239, into much smaller nuclei. This splitting releases a vast amount of energy judged by ordinary standards of comparison, such as the burning of coal or gasoline. The fission could take place spontaneously, but it is initiated deliberately by directing a stream of neutrons into a mass of uranium or plutonium which is properly arranged and is of the proper size. If an atom of fissionable material captures a neutron, it may fission into two smaller pieces. The fission of just one nucleus releases only a tiny amount of energy--too little to be measured by conventional means. However, even a small amount of material contains a vast number of atoms. When the small energy release from one fission is multiplied by the number of fissioning atoms, the total energy release is enormous.



There are different reactions which can occur in fissioning; that is, not every atom which fissions forms the same product nuclei. A few examples of fission reactions known to occur are the following:



A generalized equation can be written to represent the fission process, making use of the symbol "FP" to stand for any fission product. This equation is:

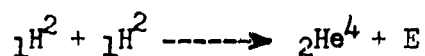


The energy released in any nuclear reaction, such as the generalized fission reaction above, comes from the conversion of mass into energy. If one were to add up the measured masses of the materials on the right side of this equation and those on the left side, he would find that the total mass on the right is less than the total mass on the left. Some mass appears to have been "lost"; this mass has been converted into energy. Einstein predicted as early as 1905 that mass and energy could be interconverted and that the relationship between them was given by the equation  $E = mc^2$ , wherein  $E$  = energy equivalent to mass  $m$ ,  $m$  = mass equivalent to energy  $E$ , and  $c$  = the speed of light. Calculations with this equation show that a very small amount of mass is equivalent to a large amount of energy. This conversion of mass into energy provides the enormous energy release from nuclear weapons.

In the generalized fission reaction equation presented above, there are two neutrons released for every one that enters. This figure of two neutrons released is a rough average for the whole set of possible fission reactions. The release of additional neutrons in the fission reaction permit the development of the chain reaction which occurs in a fission weapon or a nuclear reactor. Each neutron released is potentially able to produce another fission. Since each neutron which produces a fission leads to the release of approximately two (2.46) more neutrons, the number of fissions in each step (generation) of fissions is greater than the number in the preceding generation. Thus, the reaction builds up until the energy release is sufficient to destroy the casing of the weapon and detonation takes place.

#### 1.4.2 FUSION

A process which is the exact opposite of fission is also capable of releasing great quantities of energy. This process occurs at the lower end of the scale of elements and involves uniting two small atoms into one larger atom. This is the fusion process. Although numerous reactions are possible, the equation which follows will illustrate the nature of the reaction:



On a basis of weight of fuel necessary, this reaction produces several times the energy release of fission and does not produce residual radioactive products.

#### 1.5 CHAIN REACTION - CRITICALITY

The release of two or more neutrons at each fission makes the chain reaction possible. In order to create a chain reaction, certain conditions must be satisfied. If one of the atoms in a piece of fissionable material ( $\text{U}^{235}$ ) is caused to fission by bombarding it with a neutron, the two neutrons produced by the fissioning could do one of three things:

1. Strike other uranium nuclei and cause them to fission.
2. Pass between the uranium atoms and completely escape from the piece of material without causing any further fission. (Remember that atoms are largely empty space.)
3. Strike nuclei (uranium or impurities) and not cause fission; in other words, be captured by the nuclei.

For a chain reaction to occur, at least one of the neutrons produced per fission must strike a uranium nucleus and cause another fission to occur. In order to make this happen, we must minimize the escape and nonfission capture. Nonfission capture may be minimized by using very pure fissionable material because impurities tend to capture the neutrons and prevent fission. Escape may be minimized by having sufficient fissionable material available.

To visualize this, imagine a small, one-inch diameter spherical piece of fissionable material, in which a fission occurs. There are relatively few nuclei available within the fissionable material that the two neutrons produced by the fission may hit before they escape. Therefore, the probability of their striking other fissionable nuclei is very slight. If one of the neutrons happens to strike a nucleus and thereby causes it to fission, the probability of one of the second pair of neutrons striking a nucleus before escaping is very slight. Therefore, the reaction will quickly die down. A reaction of this type is called nonsustaining. A piece of fissionable material such

as this is called a subcritical mass (Figure 1.5).

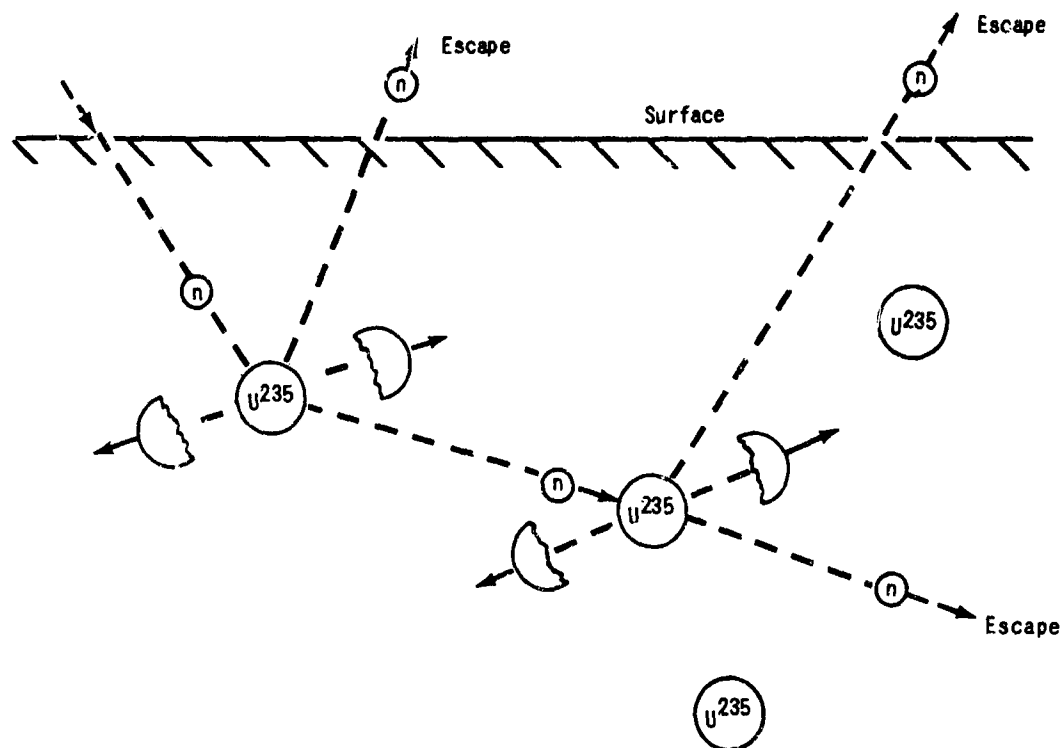


Figure 1.5 Nonsustaining chain reaction in a subcritical mass

If more material is added around the sphere, the neutrons have more nuclei which they may hit before they escape and the probability of their striking nuclei is much greater. If enough fissionable material is present so at least one neutron from every fission strikes another nucleus and causes it to fission, the reaction will continue in a steady manner and is called a sustaining chain reaction (Figure 1.6). A piece of fissionable material in which a steady reaction occurs is called a critical mass. Energy is released in a steady controllable manner, such as in a nuclear reactor used for producing power.

If still more material is added to the sphere, more than one neutron per fission may strike a nucleus to cause further fission.

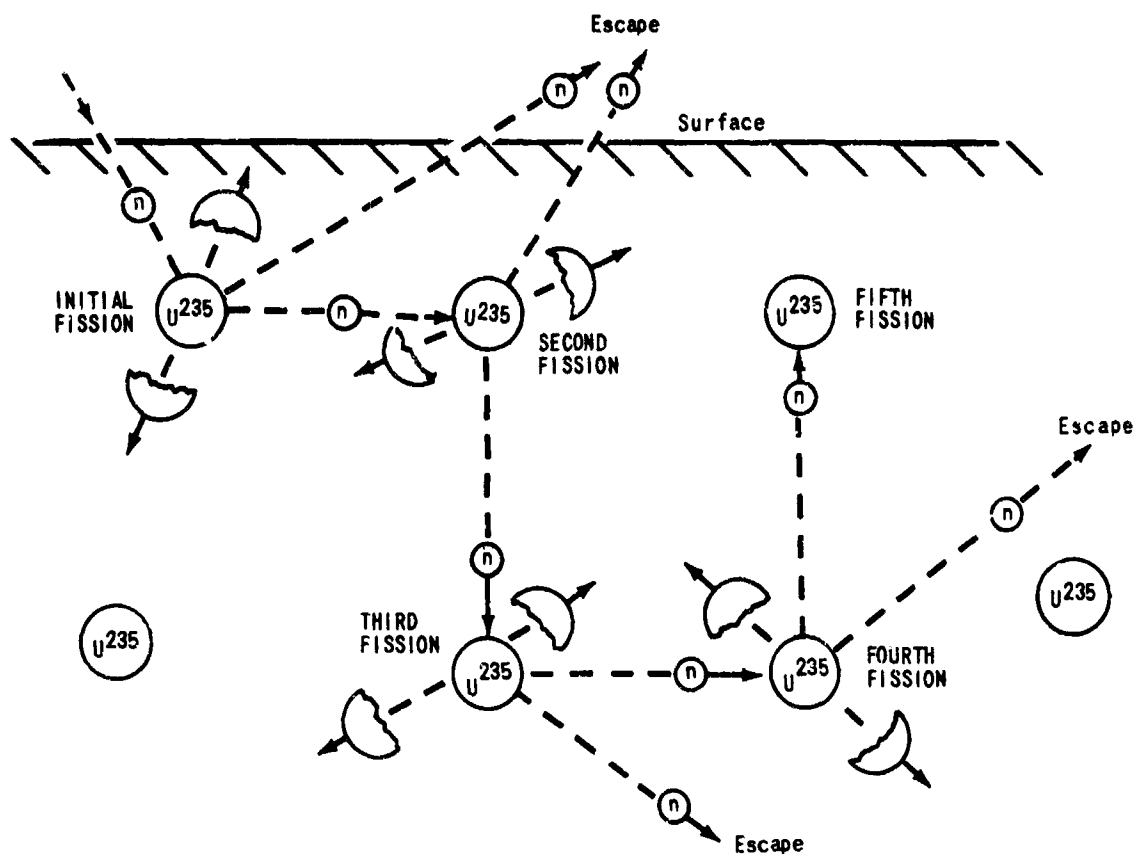


Figure 1.6 Sustaining chain reaction in a critical mass

When this occurs, the chain reaction will increase very rapidly and is called a multiplying chain reaction (Figure 1.7). In this case, we have what is known as supercritical mass. The energy is released very quickly and cannot be controlled.

## 1.6 NUCLEAR WEAPONS

### 1.6.1 GUN-TYPE

A supercritical mass is necessary to cause a nuclear detonation. However, it is unsafe to assemble a supercritical mass of fissionable material until the moment the explosion is desired, since there are always stray neutrons which could start a chain reaction. To overcome this difficulty, the fissionable material may be kept in two separate subcritical masses within the weapon. When desired, these two pieces can be brought together to form a supercritical mass which then detonates. Weapons employing this principle are known as "gun-type" weapons because one of the

subcritical masses is actually shot through a gun tube into the other subcritical mass when the explosion is desired (Figure 1.8).

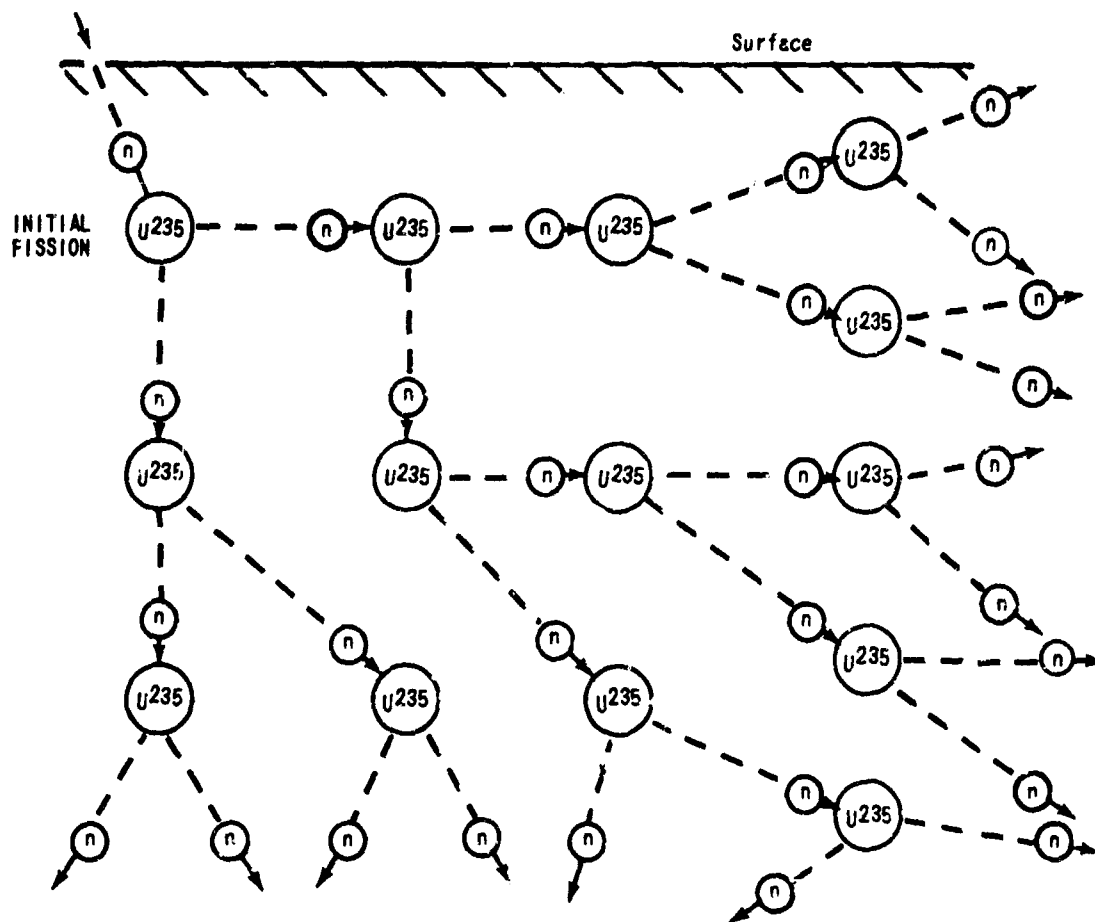


Figure 1.7 Multiplying chain reaction in a supercritical mass

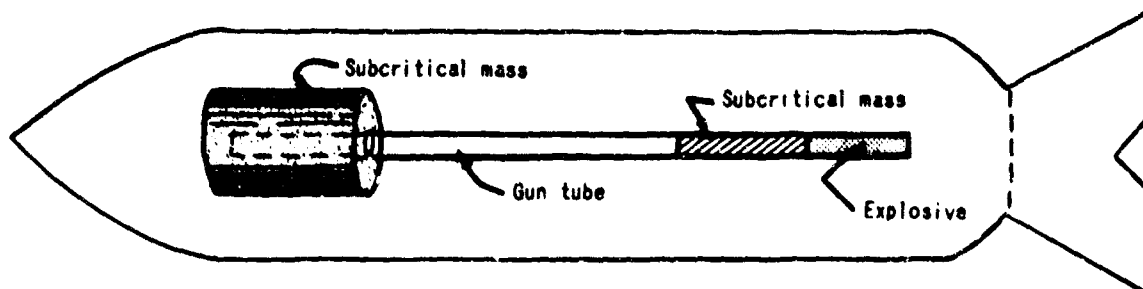


Figure 1.8 Gun-type nuclear weapon

### 1.6.2 IMPLOSION TYPE

If, instead of adding more material to a subcritical mass, the subcritical mass is compressed so that the ratio of surface area to mass becomes smaller, fewer neutrons will escape from the reduced surface area and the mass will become supercritical. This principle is also employed in nuclear weapons. A subcritical mass is surrounded by a charge of high explosive. When the explosive is detonated, the pressure created compresses the fissionable material, making it supercritical, causing it to explode. Weapons employing this principle are known as "implosion" weapons (Figure 1.9) as the high explosive is arranged so that it implodes or exerts the major portion of its explosive force inward.

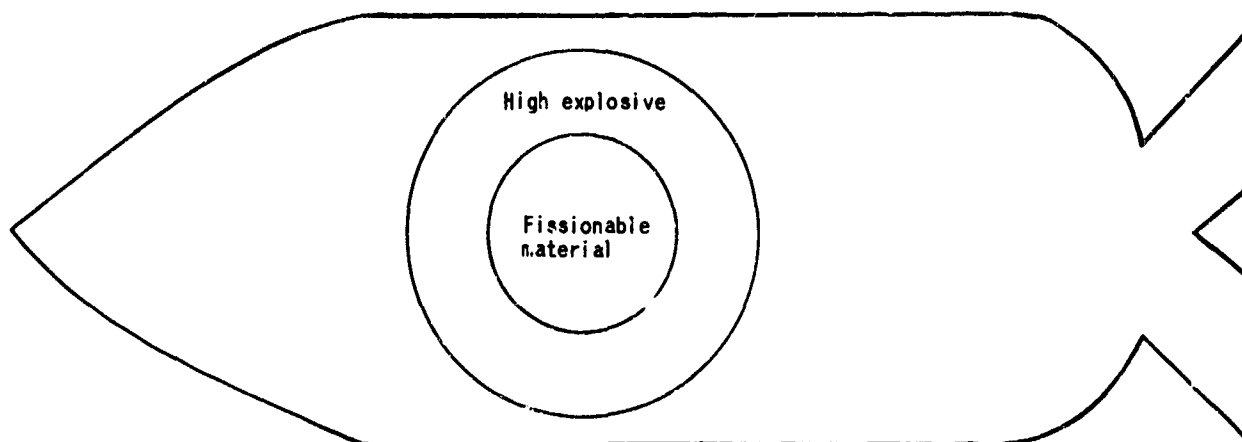


Figure 1.9 Implosion-type nuclear weapon

### 1.6.3 THERMONUCLEAR

Thermonuclear or "hydrogen" weapons utilize the fusion process to release energy. The thermonuclear reaction will occur only when the fusion fuel is subjected to enormous temperatures and pressures. At present, these can only be obtained from a fission detonation. Thus, every thermonuclear weapon has a fission "trigger" to initiate the fusion reaction.

The fusion reaction has several advantages. The fuel required is relatively cheap, and the supply is unlimited. Also, the residual products of the fusion reaction are not radioactive. The radioactivity which results from the detonation of a fusion weapon comes from the fission products of the fission component used to initiate the fusion reaction and also from neutron-induced activity. By reducing the size of the fission component as much as possible, the residual radioactivity can be reduced, thus producing a "cleaner" bomb.

## 1.7 NUCLEAR WEAPONS EFFECTS

DA Pamphlet 39-3, ENW April 1962, provides information on nuclear weapons effects. A summary of the E.N.W. presentation is given below to aid in the background study of such effects.

### 1.7.1 GENERAL KNOWLEDGE

Chapters 1, 2, & paragraph 11.77 through 11.220 in chapter 11.

Chapter 1 covers characteristics of Nuclear Explosions to include a description of the different effects of a nuclear explosion, source of nuclear power, types of nuclear explosives, scientific basis of nuclear explosions and resultant fission products.

Chapter 2 contains descriptions of different type nuclear explosions, to include air, surface, underwater, and under surface bursts; characteristics of the nuclear explosions including fire ball dimensions, blast radii, and thermal aspects.

Paragraph 11 covers Nuclear Radiation Injury, levels of dosages and corresponding injuries received, radiation of both early and delayed fallout.

### 1.7.2 WORKING KNOWLEDGE

Chapter 9 with emphasis on paragraph 9.18 through 9.30.

Chapter 9 contains the sources of Residual Radiation, calculation of dose rates of fallout, at any time after blasts.

Familiarity with the remainder of the reference to gain knowledge of the type and scope of information available.

## CHAPTER 2

### ATTENUATION OF NUCLEAR RADIATION

#### 2.1 INTRODUCTION

Nuclear Radiations are attenuated by passage through any mass. The amount of attenuation is dependent on the type and thickness of the mass and the form and energy of the incident radiation. Further, there are several different ways in which radiation is attenuated, and there is a wide range of effectiveness of specific elements for stopping different types of radiation.

A principle attenuating action is absorption, or capture, of the high energy particles (alpha, beta, or neutron) or the gamma ray. This process results in ionization which destroys living cells, but, also permits ready detection and measurement of the radiation. Alpha and beta particles are readily attenuated and are consequently of no concern in shelter analysis. As neutrons are not emitted by fallout, fallout radiation attenuation is concerned only with gamma rays. The reaction of the high speed particles is important, however, for a full understanding of gamma ray attenuation.

#### 2.2 ATTENUATION OF ALPHA AND BETA PARTICLES

##### 2.2.1 INTERACTION BETWEEN ALPHA PARTICLES AND MATTER

An alpha particle moving through matter faces a vast number of atoms along its path. Figure 2.1 illustrates an interaction between an alpha particle and an atom of carbon-12 ( ${}_{6}C^{12}$ ) as might occur in wood. The normal, neutral carbon atom with the alpha particle approaching it is shown in 2.1a. When a positively charged particle such as the alpha particle is in the vicinity of a negatively charged particle (an orbital electron), there is a strong force of attraction between the two particles. As a result of the attractive force, the electron may be pulled out of its orbit (this does not happen with every atom near which the alpha particle passes) and be released as a free-moving electron traveling at considerable speed. If this occurs, the carbon atom is no longer electrically neutral, since it has six protons in the nucleus and only five electrons outside the nucleus. The atom has a net charge of +1 and thereby is a positive ion. A positive ion is an atom with a net positive charge as the result of the removal of electrons from the neutral atom. Although strictly speaking the electron which was removed from the atom is not an ion, it is customary to refer to it as an ion in this context because it is a charged particle. Production of ions is termed ionization. The atom which has become ionized and the electron that was removed are referred to as an ion pair. The



ionization process and the terms used are illustrated in Figure 2.1.

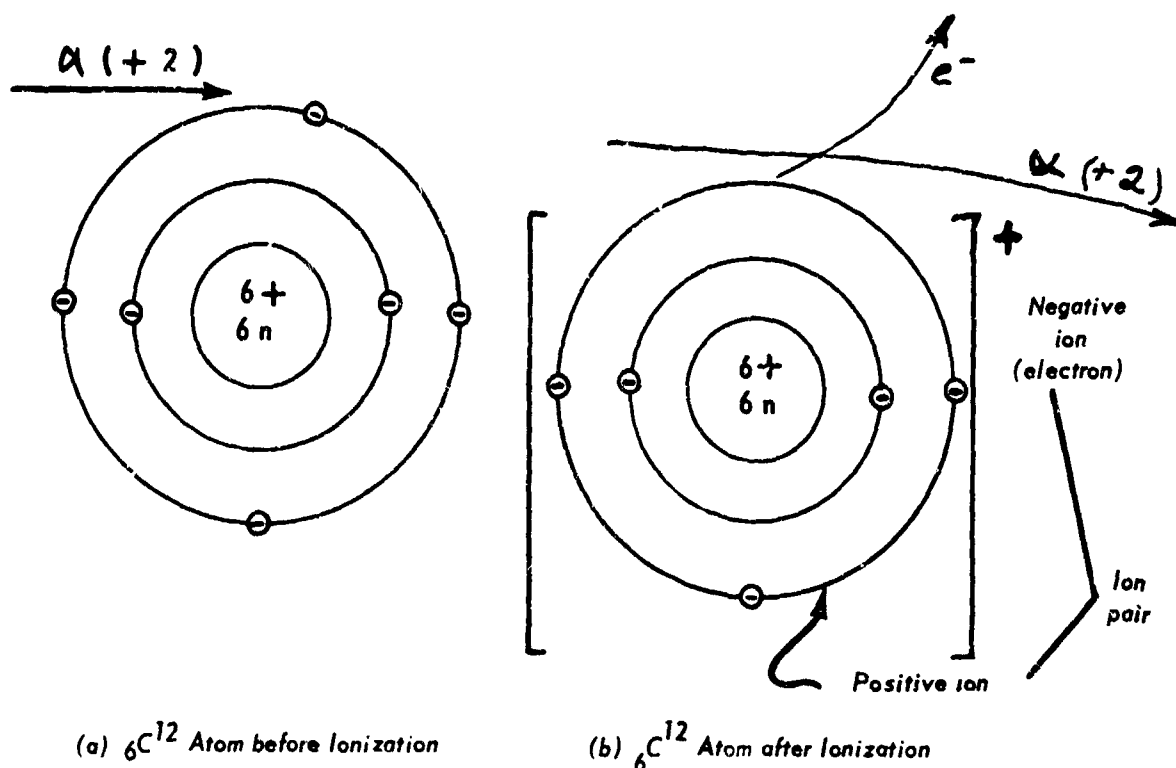


Figure 2.1 Interaction of alpha particle with orbital electrons

### 2.2.2 ENERGY CONSIDERATIONS IN IONIZATION

There is an attractive force between the electrons and the nucleus of an atom; therefore, if the alpha particle is to "pull" an electron away from the atom, it must exert sufficient force to overcome the attraction of the nucleus. The alpha particle expends some of its energy in doing the work of removing the electron; in addition, it imparts energy to the electron, which appears as kinetic energy (energy due to motion) of the off-going electron. Each time an alpha particle causes an ionization, it loses a little of its kinetic energy. As a result, its speed decreases continuously until finally it reaches equilibrium with other atoms in the matter and picks up two stray electrons to form a neutral helium atom. The distance from the source at which the alpha particle ceases to produce ionization is called its range. The range differs with different absorbing materials and with varying initial energies of the alpha particle.

In summary, the ultimate result of the passage of alpha particles through matter is ionization. The alpha particle is not usually absorbed but becomes a helium atom after loss of its energy to electrons.

### 2.2.3 INTERACTION BETWEEN BETA PARTICLES AND MATTER

When the negatively charged beta particle passes close to a negatively charged electron in passing through matter, there is a force of repulsion between the two electrons. This force of repulsion may push the orbital electron out of its position in the atom. If the electron is pushed out of the atom, an ion pair is formed. Each time an ionization occurs, the beta particle gives up energy in the form of work to remove the electron from its orbit and in the form of the kinetic energy of the displaced electron. As a result, the beta particle slows down until it reaches equilibrium with its environment. The distance from the source at which this occurs is the range of the beta particle. The range of the faster, smaller beta particle is much greater than that of an alpha particle of the same energy. Note that although the mechanism is somewhat different from that for alpha radiation, the net effect of the interaction of beta radiation with matter is the same, transfer and loss of energy through ionization.

## 2.3 INTERACTION OF GAMMA PHOTONS WITH MATTER

### 2.3.1 GENERAL

The mechanisms by which gamma radiation produces ionization differ appreciably from those of alpha or beta particles. Gamma radiation has neither charge nor mass. The results of some experiments with gamma radiation can best be explained by considering that it is a wave which transmit energy through space. However, the results of experiments such as those involving the interaction between gamma rays and atoms, can best be explained by considering the gamma rays to consist of a stream of tiny bundles of energy. Each bundle has zero mass, but is able to produce effects as though it were a particle. Each of these little "bundles" of energy is termed a photon, or quantum, of radiation. This dual wave-particle nature of electromagnetic radiation has been found to be a satisfactory explanation for the various possible interactions of electromagnetic radiations with matter and with electric and magnetic fields. The principle gamma photon-matter interactions are: (1) photoelectric effect; (2) Compton effect; and (3) pair production.

### 2.3.2 PHOTOELECTRIC EFFECT

In the photoelectric effect, a gamma photon is completely absorbed by an orbital electron. This electron has an increased kinetic energy and escapes the atom thereby creating an ion pair. This effect is illustrated in Figure 2.2.

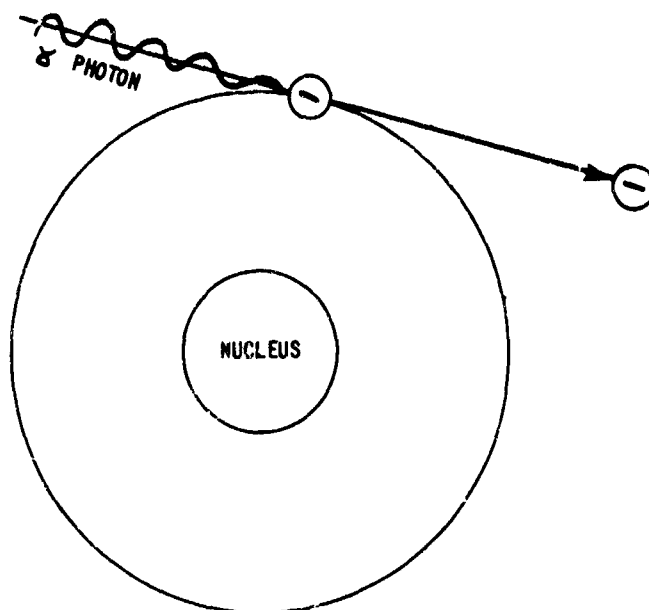


Figure 2.2 Photoelectric Effect

The electron behaves as a beta particle and can cause further ionizations by repelling electrons out of the orbits of other atoms. The original ionization produced by the gamma photon is called primary ionization; the ionizations produced by the freed electron are called secondary ionizations. (Similar statements apply to electrons released by alpha and beta particles, but in these cases secondary ionizations are of much less importance.) The secondary ionizations are much more numerous than the primary ionizations when gamma photons interact with matter.

### 2.3.3 COMPTON EFFECT

Under some conditions an incoming photon is not completely absorbed by the electron, but continues as a lower energy gamma photon. This effect, illustrated in Figure 2.3 is the Compton Effect (after Dr. Arthur H. Compton). As in the photoelectric effect, the off-going electron may produce many further ionizations. The remaining lower energy photon may undergo further Compton effects, but the last interaction resulting from it (the one in which the low-energy photon is completely absorbed) must

be a photoelectric effect. Most of the "skyspine" and wall-scatter components of radiation with which you will work in fallout shelter analysis are a result of Compton scatterings. Two important characteristics of Compton scatter are: (1) the resultant photon and beta particle have a tendency to travel in the same direction as the original gamma photon, and (2) the greater the angle of scatter, the greater the energy loss of the gamma photon.

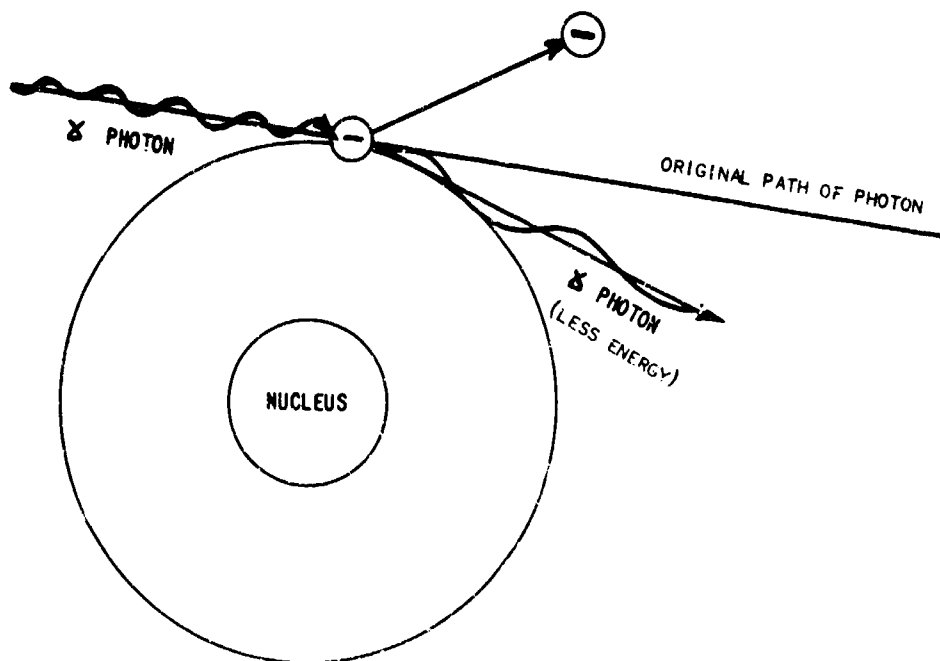


Figure 2.3 Compton Effect

#### 2.3.4 PAIR PRODUCTION

The principle third interaction of gamma photons with atoms differs considerably from the photoelectric and Compton effects. If a photon with energy (greater than 1.02 MEV) passes close to a large nucleus (such as that of lead), it can be converted into two particles, an electron and a positron (shown on Figure 2.4). The positron is a particle identical with the electron in mass, but with a positive electrical charge. The photon is eliminated in the process as all of its energy is converted into the mass of the two particles and their kinetic energy. In chapter 1, the equivalence between mass and energy and the conversion of mass into energy in the processes of fission and fusion were discussed. In pair production, the reverse process takes place in that energy

is converted into mass. The created electron and the positron are capable of producing ionizations in their paths, the electron behaving as a beta particle and the positron behaving much as an alpha particle. The positron is not a stable particle; when it loses most of its kinetic energy, it combines with an electron to produce two 0.51 MEV photons, annihilating both particles. These characteristic 0.51 MEV photons which travel in 180° opposite paths are called "annihilation radiation".

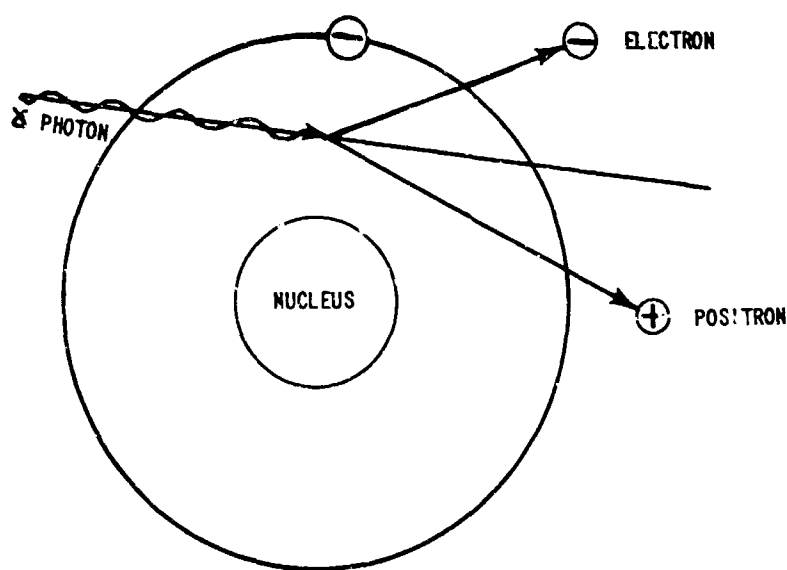


Figure 2.4 Pair Production

#### 2.3.5 SUMMARY OF GAMMA PHOTON INTERACTIONS

Although ionization is not the immediate result of pair production; it is the eventual result. Thus the three principle effects, photoelectric, Compton, and pair production, cause ionization of atoms in the material through which the gamma photons pass. The probability of occurrence of any of these events is a function of photon energy and absorber density and atomic number. Photoelectric absorption is most prominent with low energy photons in absorbers of high atomic number. Compton scattering predominates with intermediate photon energies (about 0.5-1.5 MEV) in absorbers of low atomic numbers. Pair production is significant with high energy photons in absorbers of high atomic number. Compton scattering is the principal mechanism of attenuation in fallout shelters since photon energies are in the intermediate range and most construction materials are made up of light elements.

## 2.4 ATTENUATION OF NEUTRONS

Neutrons, having no charge, do not cause ionization directly. Instead, ionization results indirectly from several processes, some of which are outlined below:

- a. Neutrons are capable of striking the nuclei of small atoms such as hydrogen and knocking these nuclei free of the orbital electrons. For example, if the nucleus of a hydrogen atom (a proton) were knocked free with a great deal of energy, it would cause ionization in the same manner as an alpha particle. This is the principal cause of biological damage from neutron radiation.
- b. Neutrons may be captured by nuclei with the instantaneous emission of gamma photons as described in paragraph 2.3. These photons can cause ionization in the same fashion as any other gamma photon.
- c. Neutrons may be captured by nuclei in an object bombarded by neutrons to form new isotopes of the original elements. These new isotopes are generally unstable (radioactive) and give off beta and gamma radiation, which will cause ionization in the manner already described.

Since there are no neutrons in fallout radiation, they are not a factor in fallout shelter analysis. Neutron radiation must be considered, however, in design of shelters to protect against initial effects. The complexity of neutron reactions is so great that empirical methods must be used in analysis for these shelters.

## 2.5 ATTENUATION OF GAMMA PHOTONS

### 2.5.1 NARROW BEAM ATTENUATION

Attenuation Formula: Unlike charged particles, which have a definite range in an absorber, gamma photons are absorbed in "one shot" processes so that any single photon may be absorbed at any point or not be absorbed at all. Gamma ray attenuation is thus based on probabilities of photon interaction. The result is a mathematical expression similar to that used for radioactive decay.

If a narrow beam of parallel, gamma rays of a single energy level (monoenergetic) are passed through an absorber, the beam intensity (I) can be expressed as a function of absorber thickness (X), in the following expression:

$$I = I_0 e^{-\mu X} \quad (2.1)$$

where  $I$  = intensity of the beam after passing through a thickness  $X$  of absorber

$I_0$  = original intensity

$X$  = absorber thickness

$e$  = base of the natural logarithms, a constant

$\mu$  (mu) = the linear absorption coefficient

#### 2.5.2 LINEAR ABSORPTION COEFFICIENT

The linear absorption coefficient,  $\mu$ , in equation 2.1 determines the rate of reduction with absorber thickness of the intensity of the beam. It can be obtained experimentally and is a function of both absorber material and the energy of the incident radiation. It increases with increasing density and atomic number of absorbers, and decreases with increasing gamma energies. Tabulations and graphs of absorption coefficients may be found in references such as the RADIOLOGICAL HEALTH HANDBOOK. A brief tabulation of  $\mu$  for common materials is given on page 397 of the ENW, 1962.

#### 2.5.3 GRAPHICAL REPRESENTATION

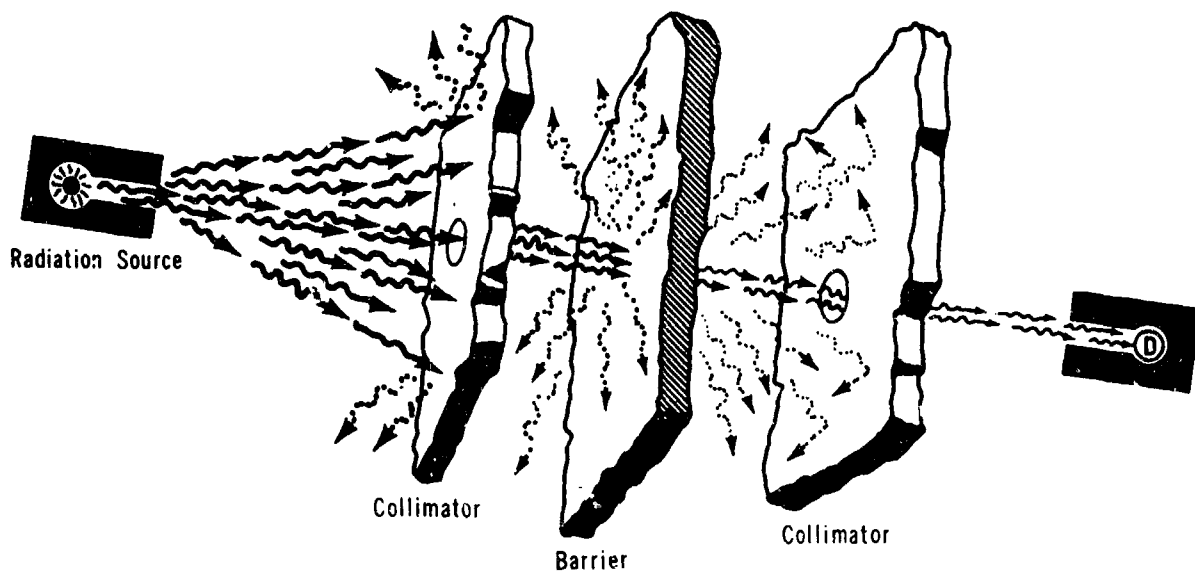
Use of the linear absorption equation is awkward due to its exponential form. It is usually more convenient to plot the results for a particular absorber and radiation on a semi-logarithmic graph, on which the function reduces to a straight line with a slope equal to  $\mu$ . An example of such a plot is presented in Figure 2.5. Note that the ratio  $I/I_0$  is plotted so that results are read in terms of a fraction of the original intensity. Problems can be readily solved from such a plot while their algebraic solutions would present difficulty due to the exponents and logarithms involved in the formula.

#### 2.5.4 BROAD BEAM ATTENUATION

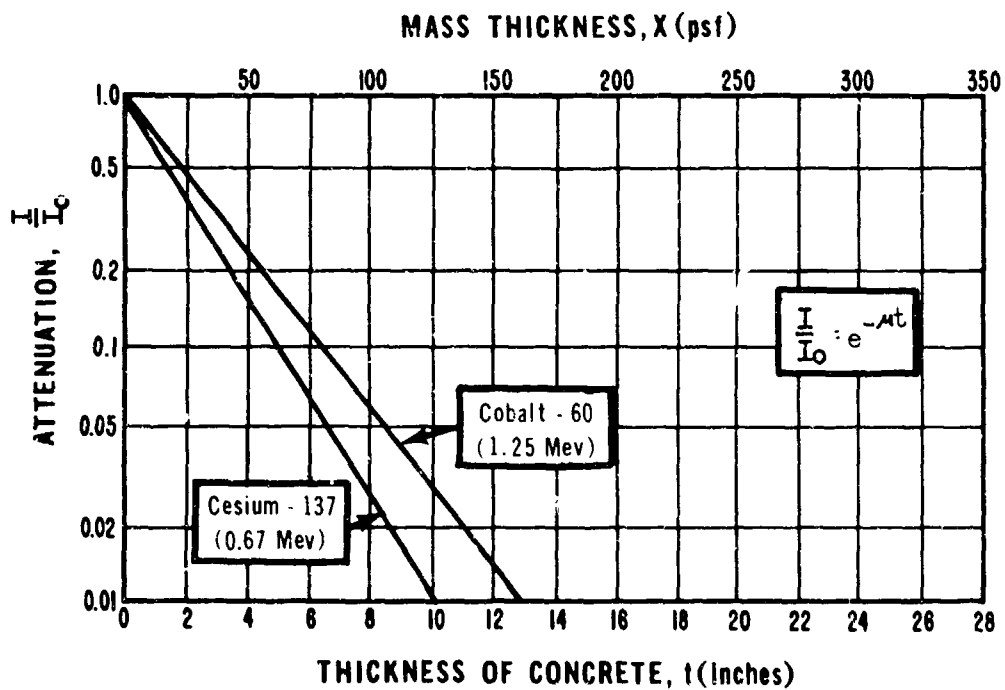
The formula for absorption  $I/I_0 = e^{-\mu X}$  (2.2)

is valid only for narrow beams of mono-energetic photons moving parallel. Any effect which scatters a photon from the beam removes it from consideration. In a more realistic situation, as in the experiment illustrated in Figure 2.6a, scattering events add to the radiation received by the detector, thus increasing the intensity for a given absorber thickness over that which would be expected in the narrow beam situation. To account for this increase, a buildup factor is added to the equation:

$$I/I_0 = B e^{-\mu X} \quad (2.3)$$



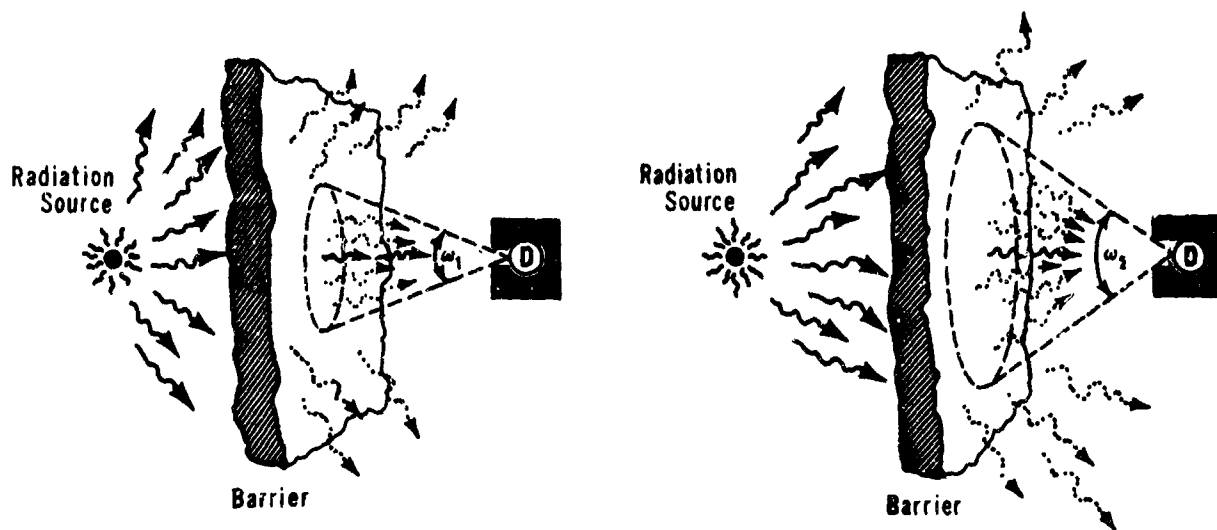
(A.) TEST ARRANGEMENT



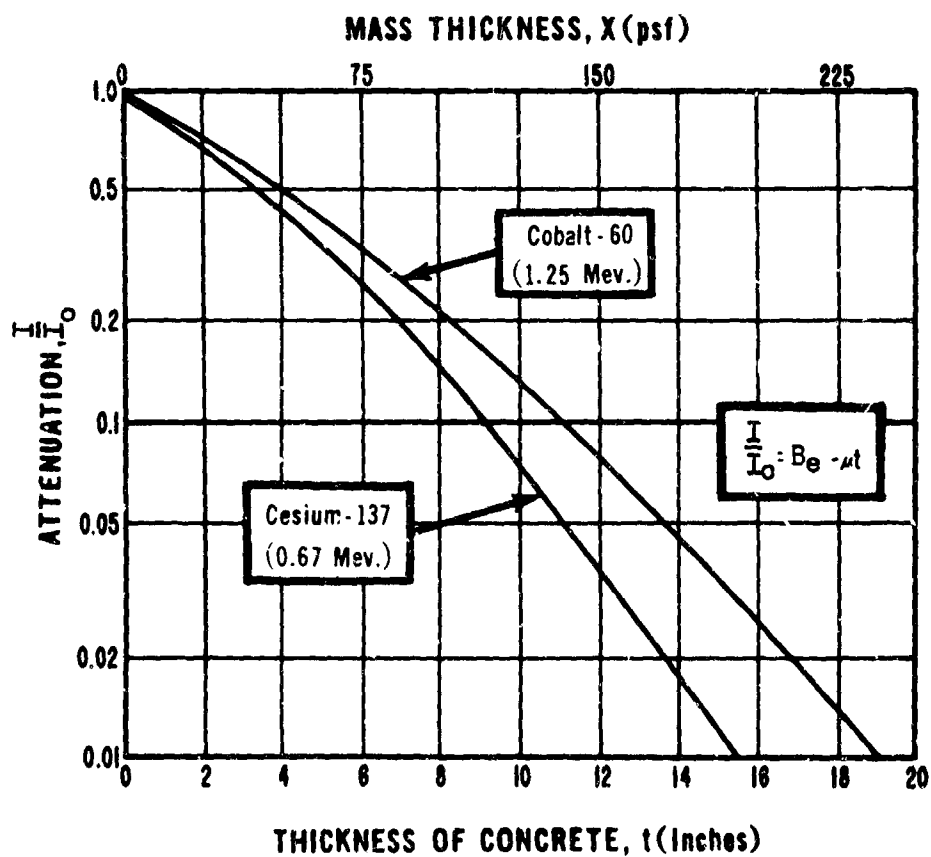
(B.) TEST RESULTS

Figure 2.5 Narrow Beam Test





(A.) TEST ARRANGEMENT



(B.) TEST RESULTS

Figure 2.6 Broad Beam Test

in which the symbols are the same as in the narrow beam equation, with the addition of the buildup factor, B. The buildup factor, a function of absorber material and gamma energy, can be determined experimentally or in some cases, developed theoretically. Note that in the case presented in Figure 2.6b, the curve departs slightly from a straight line.

#### 2.5.5 EFFECT OF DISTANCE

Imagine a point source of radiation in a vacuum, emitting  $S_0$  photons/sec in all directions. If there is an imaginary sphere of radius  $R_1$  about the point source (Figure 2.7),  $S_0$  photons/sec will pass through the surface of the sphere.

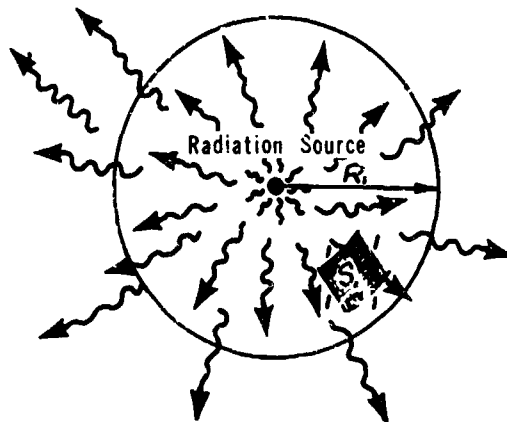


Figure 2.7

If  $S_1$  photons/sec pass through a unit area of the sphere:

$$S_1 = \frac{S_0}{4 \pi R_1^2} \quad (2.4a)$$

For a larger sphere with radius  $R_2$ :

$$S_2 = \frac{S_0}{4 \pi R_2^2} \quad (2.4b)$$

If  $S_0$  is eliminated by combining equations 2.4a and 2.4b:

$$\frac{S_1}{S_2} = \frac{R_2^2}{R_1^2} \quad (2.5)$$

Equation 2.5 states that intensity is inversely proportional to the square of the distance. This is the inverse square law which applies to many physical situations.

#### 2.5.6 COMBINED EFFECTS OF ABSORBER AND DISTANCE

If a point source is in an infinite medium, rather than in a vacuum, the intensity will vary with distance due to both absorption and the inverse square law. The equations governing both effects can be combined in a general expression using  $r$  as the distance from the source:

$$\frac{I}{I_0} = \frac{Be^{-\mu r}}{4 \pi r^2} \quad (2.6)$$

Contribution of point sources can be integrated to develop functions for plane sources in special situations of geometry. This has been done in developing the curves for the system of analysis presented in Chapter 3.

## CHAPTER 3 BASIC METHODOLOGY

### 3.1 INTRODUCTION

#### 3.1.1 OBJECTIVES

This section presents a comprehensive system for the analysis of Fallout Radiation Shielding or of vulnerability to Fallout Radiation. The objective is to present this system in concise form, with adequate illustrations of its application in elementary and complex situations.

It is not the object of this presentation to provide an illustration of every possible application of the system of analysis. Judgement of the shelter analyst is required; such judgement comes only from familiarity with the tools of analysis. Detailed methods of analysis are presented to provide the analyst with the means for developing his own engineering judgement in the subject.

#### 3.1.2 BACKGROUND

The basic system of analysis presented in this section and referred to as the "Detailed Procedure" is a modification of that formerly presented in the student text "Design and Review of Structures for Protection from Fallout Gamma Radiation". This text, prepared by Bureau of Standards and Office of Civil Defense personnel, was used for Fallout Shelter Analysis Courses given between August 1961 and August 1962. It was also referred to as the "Engineering Manual" and the system it presents as the "Engineering Manual Method of Analysis". The basis for the "Engineering Manual" was N.B.S. monograph, No. 42, by Dr. L. V. Spencer "Structure Shielding Against Fallout Radiation from Nuclear Weapons", June 1962. The system is derived from theory rather than field experimentation. Limited experimental confirmations of the basic data exist to give confidence in overall accuracy of the material; however, further research may complement or modify this material in various ways.

### 3.2 NATURE OF FALLOUT RADIATION

Fallout radiation is discussed only to the extent essential to develop the basic system of analysis. Chapter 9 of the Effects of Nuclear Weapons is a comprehensive presentation.

#### 3.2.1 FALLOUT CHARACTERISTICS

Three types of radiation are emitted by radioactive fallout material: gamma rays and fast, charged, alpha and beta particles. Neutrons are not emitted. The beta particles (electrons) can produce burns on unprotected skin; but, light shielding, such as heavy clothing, provides a high degree of protection. Alpha particles do not penetrate the skin. The charged particles are biologically destructive when the emitting sources are ingested, but they are not significant in structure shielding analysis. Gamma rays are the sole consideration in fallout shielding problems as they are extremely penetrating and biologically destructive. They may be described as high energy X-rays, but the term "gamma ray" is normally used when the radiation is emitted from the nucleus of the atom whereas X-rays originate from the orbiting electrons.

#### 3.2.2 THE STANDARD

In radiation shielding analysis, the effectiveness of shielding is measured by relation to a standard. THE STANDARD used for analysis of structures is the AMOUNT OF RADIATION THAT IS RECEIVED BY A POINT 3 FEET ABOVE AN INFINITE, SMOOTH, UNIFORMLY CONTAMINATED PLANE. This amount of radiation is normalized to unity; thus the lesser amount of radiation which is received by a detector which is shielded by mass or displacement from the source of radiation may be represented by relation to THE STANDARD, as a decimal fraction.

The contribution of radiation to a detector is determined by multiplying the effects of reduction due to barrier shielding by the effects of reduction due to geometry shielding. The sum of all contributions through various contributing surfaces of a structure, such as the exterior walls and roof, is the total contribution or total "REDUCTION FACTOR". This reduction factor is the decimal fraction of THE STANDARD that is transmitted to the detector.

The following example illustrates the significance of THE STANDARD. The REDUCTION FACTOR at a point in the center of a base-

ment fallout shelter is 0.01. Fallout occurs and at a specific time the dose rate is 100 roentgens per hour at a point 3 feet above the outside field of radiation unprotected by adjacent structures or any other shielding. This measured dose rate is thereby equivalent to THE STANDARD. Thus, the dose rate within the shelter would be  $0.01 \times 100 \text{ R/hr}$ , or 1 Roentgen per hour.

The multiplication of reduction factors due to the various effects reducing the radiation received is illustrated below:

The mass of the walls of a shelter by itself causes the incident radiation to be reduced to 20% of the magnitude of radiation received by THE STANDARD. The dimensions and orientation of the walls and the detector by themselves, cause the radiation to be reduced to 50% of the magnitude of radiation received by THE STANDARD. The barrier reduction factor for the walls is thus .20. The geometry reduction factor for walls is thus .50. The combined effect of barrier and geometry factors is  $.20 \times .50 = .10$  i.e., the detector receives through the walls an amount of radiation which is 10% of the amount that would be received by a point 3 feet above an infinite plane.

### 3.2.3 DIRECTIONAL NATURE OF RADIATION

Radiation is received at an unshielded point over a contaminated field from all directions even though all emitting sources lie upon that field. Radiation is received from above the point due to the scattering of gamma rays by the air ("Compton Effect"). Some radiation which is received from below the point is also radiation which has been scattered in the air; however, most of the radiation that is received from below the point has traveled to the point directly from the emitting sources on the ground without having been scattered. This is shown in Figure 3.1.

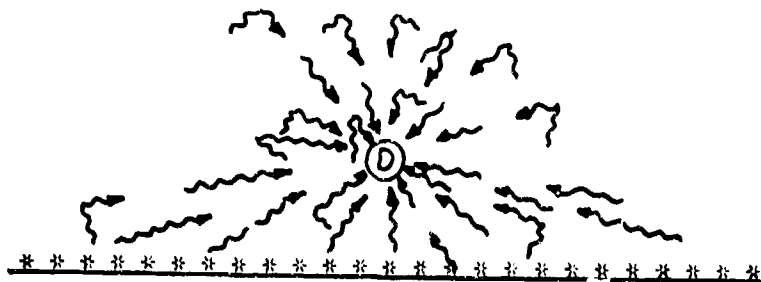
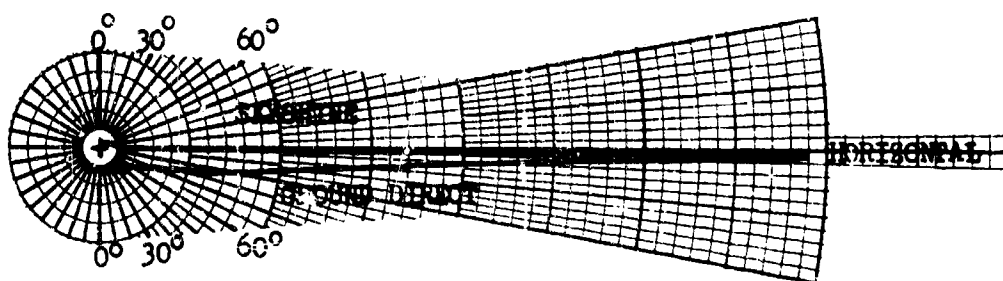


Figure 3.1 Radiation at an Unshielded Point

The radiation received by the point, or "detector" at that point, varies in intensity with the direction from which it comes. Variables which cause this effect are closeness to the emitting source, the mass of air between the emitting source and the detector, the amount of radiation which reaches the detector from a specific direction and the number of emitting sources in that direction. The result of these effects is that a point such as THE STANDARD, over a uniformly contaminated field of indefinite extent, receives radiation with a polar distribution of intensity with direction as shown in Figure 3.2. With reference to this figure, note the extreme concentration of intensity just below the level of the horizontal plane through the detector, and in general, the significantly greater proportion of the radiation which arrives from below this horizontal plane in comparison with that from above the plane.



Vector Scale: Relative magnitude of radiation received integrated 360° about the vertical axis

Figure 3.2 Directional Distribution of Radiation Received by THE STANDARD.

Radiation which arrives at the detector after having been scattered by air above the horizontal plane through the detector is termed SKYSHINE. SKYSHINE consists entirely of air scattered radiation. Radiation which arrives at the unshielded detector from below the horizontal plane through the detector is arbitrarily termed GROUND DIRECT. It should be noted that GROUND DIRECT includes radiation direct from the emitting sources on the ground and radiation which has been air scattered below the detector elevation. The radiation which is not air scattered comprises the overwhelming bulk of GROUND DIRECT.

### 3.3 SOURCES OF REDUCTION IN RADIATION RECEIVED

#### 3.3.1 DISTANCE

Radiation received by a detector from a single emitting point decreases with increased separation of detector and source. This decrease occurs in a vacuum, atmosphere, or a denser medium. The decrease due to distance alone varies as the square of the distance from the emitting source. This decrease and its cause may be represented by the intensity of radiation passing through a unit area on the surface of sphere whose center is the emitter. The number of gamma rays passing through a given unit area on the sphere is thereby dependent on the total surface area of the sphere. As the surface area of a sphere of radius,  $r$ , is  $4\pi r^2$  the fractional portion of the surface occupied by a unit area is  $\frac{1}{4\pi r^2}$ , thus representing the variation of intensity with " $r$ ".

distance dependent reduction in the amount of radiation received compared to that received by THE STANDARD, 1.0, occurs when the detector is more than 3 feet above the plane of contamination, when the detector is over a cleared area within a contaminated field of otherwise infinite extent, or when the contributing area is of finite dimensions. Distance factors are height, dimensions of the contaminated field, such as a contaminated roof, and extent of the cleared or non-contributing area, such as the floor within the building walls.

#### 3.3.2 MASS

The passage of Gamma radiation through mass has several different effects upon the Gamma radiation. In one, the "photoelectric effect", the photon of gamma radiation may be absorbed, transferring all of its energy to an electron of an atom, which is then ejected from the atom. Since the photon involved loses all of its energy, it ceases to exist. A second effect is scattering of the radiation, the "Compton Effect". In this interaction, the gamma ray photon collides with one of the atomic electrons transferring some of the energy of the photon to the electron. The photon, with its energy decreased, proceeds in a direction at an angle to its original direction of motion. The third effect is "pair production", possible with high energy gamma radiation. When a gamma ray photon with energy greater than 1.02 MEV passes near the nucleus of an atom, the photon may be converted directly into matter, with the formation of a positive and a negative electron. The photon disappears in this process, however the two particles created soon interact with other electrons forming two photons of less energy than that of the original one.

The relationships of the above reactions to the atomic number of



the material comprising the mass, to the energy of the incident gamma ray, and to the thickness of the mass are described in detail in Chapter 2 and in Chapter 8 of THE EFFECTS OF NUCLEAR WEAPONS. In summary, the magnitude of the effects, or the portion of the incident gamma rays that are affected, increase with the amount of mass. The system of analysis is directly concerned only with the overall shielding obtained and scattering. The overall shielding is determined as the fractional portion of the radiation from an area source, incident upon a barrier, that emerges from the inner face of that barrier. Reduction due to scattering in which the radiation does not emerge from the inner face is included with absorption. Further, the "Build-up Factor" for radiation which is scattered, but still emerges from the inner face of the barrier, is not separately considered.

The occurrence of scattering is considered in a differentiation of the radiation that emerges from the inside face of an exterior barrier. This is not in the form of a reduction, but only in identity of the radiation.

### 3.4 PARAMETERS OF SOURCES OF REDUCTION

#### 3.4.1 GENERAL

Shielding is reduction in radiation due to some effect. Shielding analysis is the determination of numerical values for such effects with a result that relates radiation received through shielding to the radiation received if there were no shielding effects, i.e. THE STANDARD. Shielding is the result of a complex interaction of variables, many of which may only be approximated by lengthy integral calculus or numerical procedures. Practical shielding analysis must give numerical values to terms which will approximate the actual situation. Shielding analysis consists of identifying the principle factors, measuring them, and determining their direct effect and influence on other factors.

A basic division into geometry and barrier factors is made in measurement of sources of reduction. Geometry factors are reduction factors principally due to directional distribution and distance effects. Barrier factors are primarily reduction factors due to mass.

#### 3.4.2 GEOMETRY SHIELDING

##### 3.4.2.1 Derivation of Solid Angle Fraction

The evaluation of geometry shielding effects requires calculating the size of the contributing contaminated plane or of the non-contributing surface. A roof is a limited contaminated area, while a non-contaminated or non-contributing area would

be the floor of a building within its exterior walls.

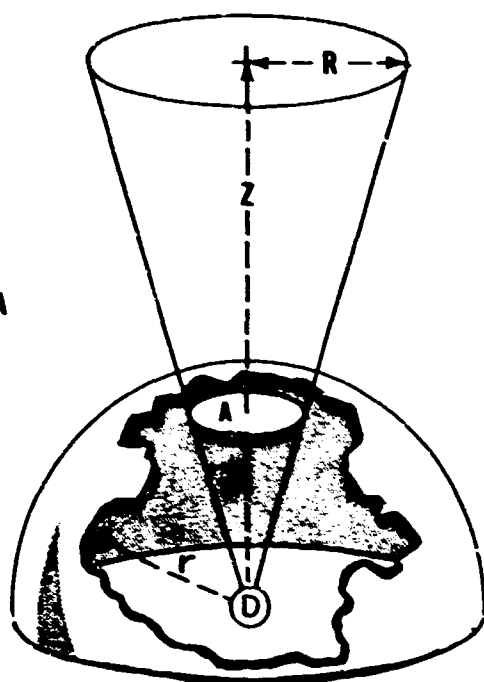
A solid angle fraction, represented by the symbol  $\omega$  (omega), defines the portion of the field of view, seen from a point of interest that is occupied by a finite plane area. The point of interest would normally be the detector. A solid angle measured at a point is an angle in three dimensional space bounded by a conical surface with its vertex at that point. A solid angle may be defined as either the angle in three dimensions or the area subtended by the bounding conical surface on the surface of a sphere of unit radius. In solid geometry, a solid angle is measured in steradians, with a total of  $4\pi$  steradians about any point. In the alternate definition, a solid angle is the area subtended on the surface of a sphere of unit radius, or the area measured in units of  $r^2$  subtended on the surface of a sphere of radius  $r$ . Figure 3.3 gives two illustrations of area subtended on the surface of a sphere by a cone or pyramid. The vertex of the cone or pyramid is coincident with the center of the sphere.

The directional nature of the radiation received by a detector, as described in 3.2.3 and shown in Figure 3.2, and the natural dividing plane between Skyshine and Ground Direct radiation at the horizontal plane through the detector make it convenient to use solid angle fraction as a fraction of a hemisphere. In Figure 3.3, the solid angle fraction of area  $W \times L$  is the area  $A$  subtended on the surface of the sphere divided by the area of the hemisphere,  $2\pi r^2$ . A plane area of infinite extent would subtend an entire hemisphere and thus would have a solid angle fraction equal to 1.0, indicating that it subtends the entire hemispherical field of view. Since a single plane surface cannot subtend more than a hemisphere, solid angle fraction will not exceed 1.0.

#### 3.4.2.2 Computation of Solid Angle Fraction

A numerical value is required for solid angle fraction determined by a finite plane area and a point of interest. As can be visualized from Figure 3.3, the limiting dimensions in the plane and the distance between the plane and point are the critical factors. Solid angle fraction is computed for areas which are symmetrically oriented about a perpendicular drawn from the point of interest to the plane of the area. Further, the numerical solution of solid angle fraction is only made for rectangular or circular areas. An area that is not symmetrical about the axis or is not circular or rectangular is treated by approximation or by multiple increments. Such situations are presented in Chapter 5.

(A.) CIRCULAR AREA



$$\omega = 1 - \cos \theta$$

where  $\tan \theta = \frac{R}{Z}$

(B.) RECTANGULAR AREA

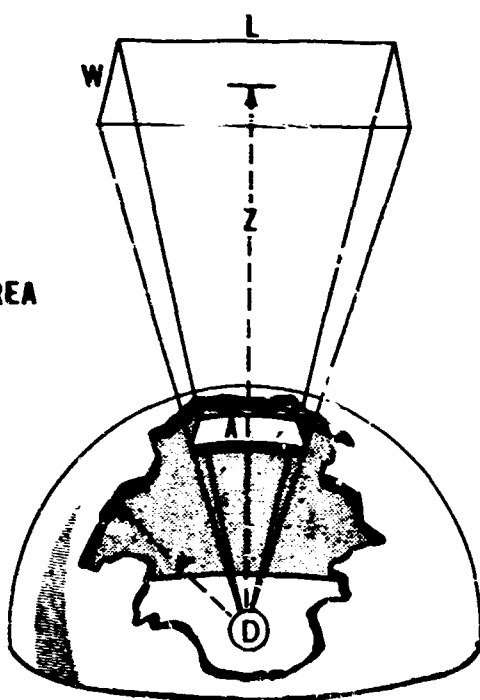


Figure 3.3 Solid Angle Fraction,  $\omega$ .

The solid angle fraction subtended by a circular area, as shown in Figure 3.4 may be computed by the exact formula

$$\omega = 1 - \cos \theta \quad (3.1a)$$

developed from the formula

$$\omega = \frac{A}{2\pi r^2} = \frac{1}{2\pi r^2} \int_0^\theta (2\pi r \sin \theta) (r d\theta) \quad (3.1b)$$

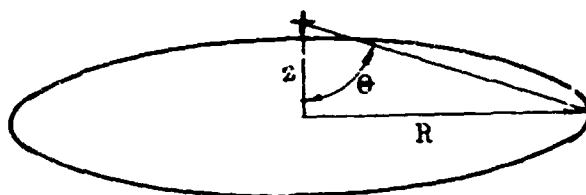


Figure 3.4 Solid Angle Fraction, Circular Area

Since:  $\tan \theta = \frac{R}{z}$  and  $\cos \theta = \frac{1}{\sqrt{1 + \tan^2 \theta}}$

the relationship:  $\cos \theta = \frac{1}{\sqrt{1 + \left(\frac{R}{z}\right)^2}}$  may be used to

simplify the calculation of  $\omega$  in absence of tabular or sliderule functions of angles. Examples 3.1 and 3.2 illustrate the use of these formulas for solid angle fraction determination.

The solid angle,  $\psi$ , subtended by a rectangular area symmetrically located with respect to the point of interest shown in Figure 3.5 is given by the expression:

$$\psi = 4 \tan^{-1} \left[ \frac{e}{n\sqrt{n^2 + e^2 + 1}} \right] \quad (3.2)$$

where:  $e$  is the eccentricity ratio =  $\frac{\text{width}}{\text{length}} = \frac{W}{L}$

$n$  is the normality ratio =  $2 \times \frac{\text{perpendicular distance from plane}}{\text{Length}} = \frac{2z}{L}$

Example 3.1 Solid Angle Fraction for a Small Circular Area

REFERENCE: Figure 3.3a

GIVEN :  $R = 15\text{ft.}$   $z = 50\text{ft.}$

$$\text{SOLUTION : } \omega = 1 - \cos \theta \quad \theta = \tan^{-1} \frac{R}{z} = \tan^{-1} \frac{15}{50} = \tan^{-1} .30 = 16.7^\circ$$

$$\omega = 1 - \cos 16.7^\circ = 1 - .958$$

$$\omega = .042$$

---

Example 3.2 Solid Angle Fraction for a Large Circular Area

REFERENCE: Figure 3.4

GIVEN :  $R = 60\text{ft.}$   $z = 3\text{ft.}$

$$\text{SOLUTION : } \omega = 1 - \cos \theta \quad \cos \theta = \pm \frac{1}{\sqrt{1 + \tan^2 \theta}} \quad \tan \theta = \frac{R}{z} = \frac{60}{3} = 20$$

$$\omega = 1 - \frac{1}{\pm \sqrt{1 + \frac{R^2}{z^2}}} = 1 - \frac{1}{\sqrt{1 + 20^2}} \approx 1 - \frac{1}{20} = 1 - .05$$

$$\omega \approx .95$$

---

Example 3.3 Solid Angle Fraction for a Small Rectangular Area

REFERENCE: Figure 3.3b

GIVEN :  $W = 15\text{ft.}$   $L = 25\text{ft.}$   $z = 50\text{ft.}$

$$\text{SOLUTION : } \omega = \frac{2}{\pi} \tan^{-1} \left[ \frac{e}{n \sqrt{n^2 + e^2 + 1}} \right] \quad e = \frac{W}{L} = \frac{15}{25} = .60$$
$$n = \frac{2z}{L} = \frac{100}{25} = 4$$

$$\omega = \frac{2}{\pi} \tan^{-1} \left[ \frac{.60}{4 \sqrt{16 + .36 + 1}} \right] = \frac{2}{\pi} \tan^{-1} .036$$
$$\omega = \frac{2}{\pi} \times .036 \quad \tan^{-1} .036 = \frac{2.06^\circ}{180^\circ} \times \pi$$

$$\omega = .0228$$

**Example 3.4 Solid Angle Fraction for a Large Rectangular Area**

REFERENCE: Figure 3.5

GIVEN :  $W = 35\text{ft.}$   $L = 50\text{ft.}$   $z = 3\text{ft.}$

SOLUTION :

$$\omega = \frac{2}{\pi} \tan^{-1} \left[ \frac{e}{n \sqrt{n^2 + e^2 + 1}} \right]$$

$$e = \frac{W}{L} = \frac{35}{50} = .70$$

$$n = \frac{2z}{L} = \frac{6}{50} = .12$$

$$\omega = \frac{2}{\pi} \tan^{-1} \left[ \frac{.70}{.12 \sqrt{.0144 + .49 + 1}} \right] = \frac{2}{\pi} \tan^{-1} 4.76$$

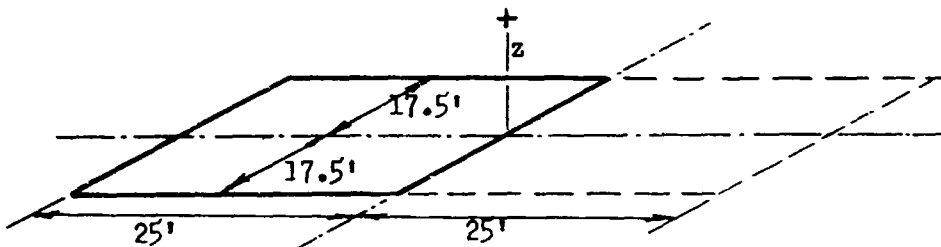
$$\omega = \frac{2}{\pi} \times 1.36$$

$$\tan^{-1} 4.76 = \frac{78.1^\circ \times \pi}{180^\circ} = 1.36$$

$\omega = .865$

**Example 3.5 Solid Angle Fraction, One Axis of Symmetry**

GIVEN : Area  $25\text{ft.} \times 35\text{ft.}$   $z = 3\text{ft.}$



REQUIRED : Find  $\omega$  of the  $25' \times 35'$  area.

REFERENCE: Example 3.4

- SOLUTION :
1. Find an area symmetrical about both axes through the perpendicular from the point of interest to the plane of the area (dashed lines in the figure).
  2. Find the solid angle fraction for the symmetrical area  $= 2\omega = .865$  (from Example 3.4).

$$3. \omega = \frac{2\omega}{2} = \frac{.865}{2}$$

$\omega = .432$

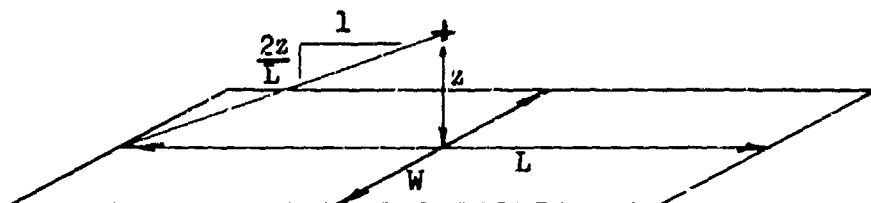


Figure 3.5 Solid Angle Fraction, Rectangular Area

The solid angle fraction  $\omega$ , then, is given by the expression:

$$\omega = \frac{\Psi}{2\pi} = \frac{2}{\pi} \tan^{-1} \left[ \frac{e}{n \sqrt{n^2 + e^2 + 1}} \right] \quad (3.3b)$$

Examples 3.3 and 3.4 illustrate the use of the above formulas for rectangular finite areas symmetrical about a perpendicular from the point of interest to the area. Example 3.5 shows the computation of  $\omega$  for a point of interest centered over one edge of the finite area.

A chart solution of  $\omega$  from this expression when  $n = 10$ ,  $e = .01$  is given in Chapter 4. The chart allows rapid determination of  $\omega$  for the usual situation of a rectangular structure. When  $e$  is less than .01, the formula must be used. Note that as one dimension,  $L$ , goes to infinity,  $\omega$  remains a determinable quantity:

the equation

$$\omega = \frac{2}{\pi} \tan^{-1} \left[ \frac{\frac{W}{L}}{\frac{2z}{L} \sqrt{\left(\frac{2z}{L}\right)^2 + \left(\frac{W}{L}\right)^2 + 1}} \right] \quad (3.3c)$$

becomes, with  $L = \infty$

$$\omega = \frac{2}{\pi} \tan^{-1} \left[ \frac{W}{2z \sqrt{0 + 0 + 1}} \right]$$

or

$$\omega = \frac{2}{\pi} \tan^{-1} \left[ \frac{W}{2z} \right] \quad (3.4)$$

When  $n$  is greater than 10, the situation is one of a very small area a large distance from the point of interest. In such situations the actual area,  $W \times L$ , of the plane finite area closely approximates the area subtended by the bounding conical surface on the surface of a sphere of radius equal

to  $z$ . Using the plane area in place of the area on the spherical surface, the following approximate expression for  $\omega$  is developed:

$$\omega = \frac{A}{2 \pi z^2} \approx \frac{W \times L}{2 \pi z^2} \quad (3.5)$$

Values of  $\omega$  given by this formula when  $n > 10$  are within the accuracy of the system of analysis and thus are fully adequate. The above expression has general application to an area of any shape which is of distance from the point of interest such that the area of the plane area approximates the area that the bounding conical surface subtends on a sphere of radius equal to  $Z$ .

The use of equations 3.4 and 3.5 is shown in Examples 3.6 and 3.7.

### 3.4.2.3 Geometry Shielding Determination

The calculation of radiation received at a point within a structure is divided into the calculation of radiation through overhead roof surfaces, termed Overhead Contribution, and that received through exterior walls, termed Ground Contribution. The overhead contribution,  $C_o$ , or reduction factor  $R_f$  (overhead), is equal to the sum of the radiation received from a given contaminated roof surface and the amount of skyshine received through the roof. The ground contribution,  $C_g$ , is the product of the barrier factors and the geometry factors. The geometry effect is dependent upon solid angle fractions.

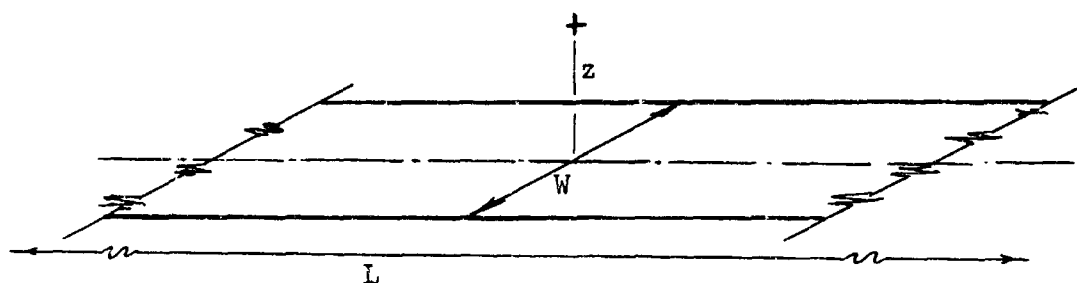
For calculation of roof contribution, the solid angle fraction is determined for the contributing area. Thus, the solid angle is determined with the detector as the vertex and the edges of the roof as limits of the contributing finite plane area. Example 3.8 includes the determination of solid angle fraction for the basic roof situation. The solid angle fraction is the geometry parameter of the overhead contribution,  $C_o$ .

The determination of contribution of radiation coming through an exterior wall uses the upper and lower edges of the wall as the limits of finite plane areas which determine solid angles with vertexes at the detector, and thus specific solid angle fractions. In the calculation of ground contribution therefore, the finite plane area determining the solid angle fraction represents the NON-CONTRIBUTING portion of the hemispherical field of view. Radiation emerging from the



Example 3.6 Solid Angle Fraction for  $L = \infty$

GIVEN :  $W = 20\text{ft.}$   $L = \infty$   $z = 10\text{ft.}$

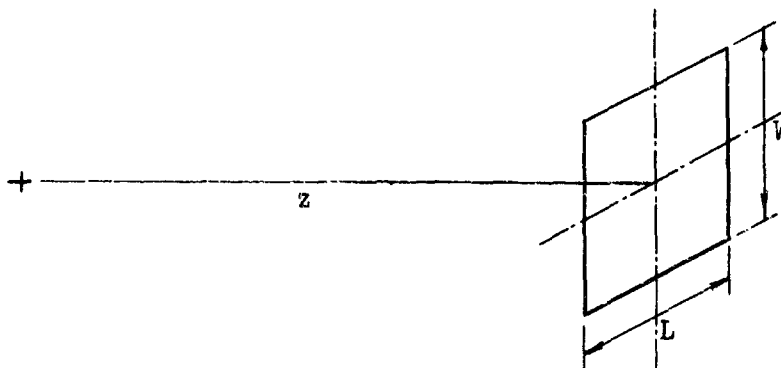


$$\text{SOLUTION: } \omega = \frac{2}{\pi} \tan^{-1} \frac{W}{2z} = \frac{2}{\pi} \tan^{-1} \frac{20}{20} = \frac{2}{\pi} \frac{\pi}{4}$$

$$\omega = .5$$

Example 3.7 Solid Angle Fraction for  $n > 10$

GIVEN :  $W = 4\text{ft.}$   $L = 5\text{ft.}$   $z = 30\text{ft.}$



$$\text{SOLUTION: } \omega = \frac{A}{2\pi z^2} \approx \frac{W \times L}{2\pi z^2} = \frac{4 \times 5}{2\pi 900}$$

$$\omega \approx .00354$$

inner face of an exterior wall is divided into NON-WALL-SCATTERED, and WALL-SCATTERED directional responses. Solid angle fraction is used as a parameter for the determination of these responses. The radiation which emerges from the inner face of the exterior wall and arrives at the detector has the following notation:

- $G_a$  - Skyshine directional response, non-wall scattered radiation from above a horizontal plane through the detector.
- $G_d$  - Ground Direct directional response, non-wall-scattered radiation from below the horizontal plane through the detector.
- $G_s$  - Wall-scattered radiation directional response, from both above and below the horizontal plane through the detector.

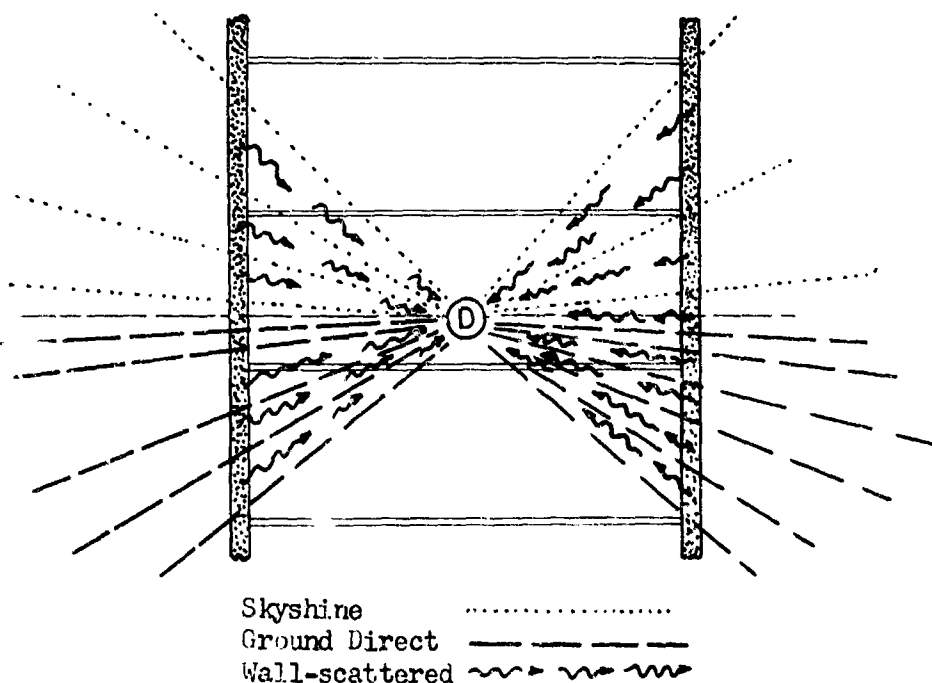
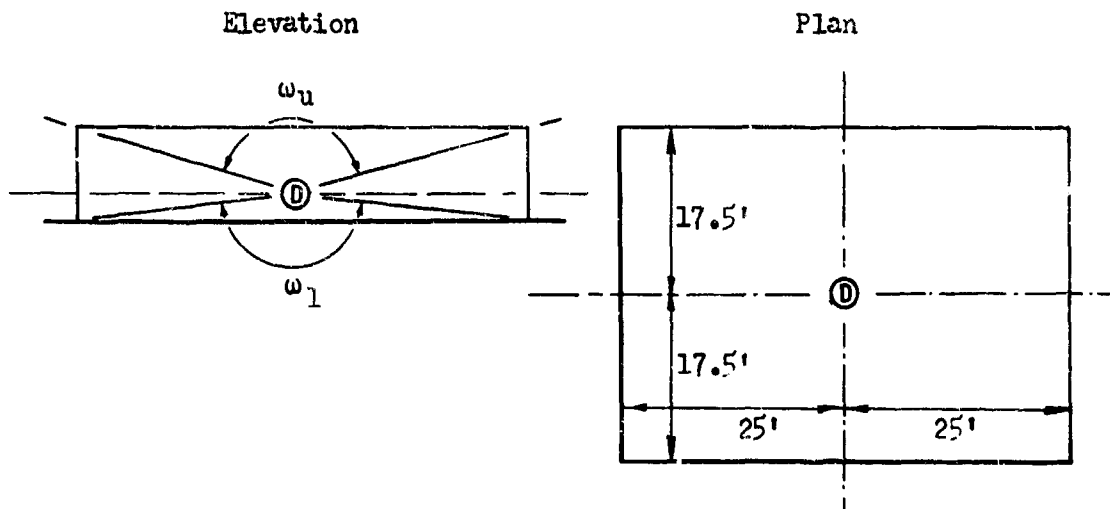


Figure 3.6 Ground Contribution Received by a Shielded Detector

This classification of the ground contribution into separately identified directional responses is shown in Figure 3.6. The floors above and below the detector

Example 3.8 Directional Responses for a Simple Structure

GIVEN :  $W = 35\text{ft.}$   $L = 50\text{ft.}$  Detector 3ft. above floor  
Wall 10ft. high



REQUIREMENT: 1. Determine values of  $\omega_u$  and  $\omega_1$ .

2. Determine appropriate  $G_d$ ,  $G_a$ , and  $G_s$ .

SOLUTION	W	L	e	z	$n = \frac{2z}{L}$	1.	2.		
						$\omega$ Chart 3	$G_d$ Chart 6	$G_a$ Chart 5	$G_s$ Chart 5
$\omega_u$	35	50	.70	7	.28	.70	none	.069	.23
$\omega_1$	35	50	.70	3	.12	.86	.48	none	.155

limit the exterior walls and thus form finite, plane non-contributing areas. The magnitude of the contributing areas may be represented as the sum of the portions of the upper and lower hemispheres which are not subtended by the solid angle fractions. As directional responses are determined as the contribution through the portion of the hemisphere not subtended by the solid angle, they are functions of a single solid angle fraction. Directional responses will vary counter to variation in the solid angle fraction. Directional responses for a simple structure are determined in Example 3.8 by use of charts 5 and 6, in Chapter 4.

Directional responses determined from charts 5 & 6 in Chapter 4 are for the "pure" situations of the radiation emergent from the inner face of the exterior wall being either all non-wall-scattered radiation or all wall-scattered radiation. Such pure situations do not exist in practice except for an opening in a wall. In cases of windows and light doors, the mass thickness is assumed to be negligible and consequently, these are analysed as pure situations with only non-wall-scattered radiation.

In the typical exterior wall shielding situation both non-wall-scattered and wall-scattered radiation emerge from the inner face of the wall. The fraction of the emergent radiation which has been scattered in the wall is a function of the mass thickness of the exterior wall. Values of wall-scattered radiation, the sum of the  $G_w$  and non-wall-scattered radiation,  $G_d$  plus  $G_w$ , which are determined as though for pure situations are reduced by multiplication by the fraction of the emergent radiation which has been or has not been scattered in the wall, respectively. As the fraction which has been scattered is represented by  $S_w$ , then the fraction of the emergent radiation which has not been scattered is  $1-S_w$ .

The wall-scattered radiation received from an exterior wall varies with the orientation of the wall with respect to the detector. Collimation of radiation scattered in the wall increases the proportion of the total wall-scattered radiation that comes from the adjacent wall. Thus, a detector between two parallel walls which extend to infinity receives radiation from the full extent of both walls, but receives the bulk of this radiation from those portions of the walls adjacent to normals drawn to those walls from the detector, (shown in Figure 3.7a). A situation which departs from this case, such as a rectangular structure (Figure 3.7b) has less wall area from which the radiation may emerge; but since the detector is now opposite points on four walls, has a larger total of wall-scattered contribution to the detector. The

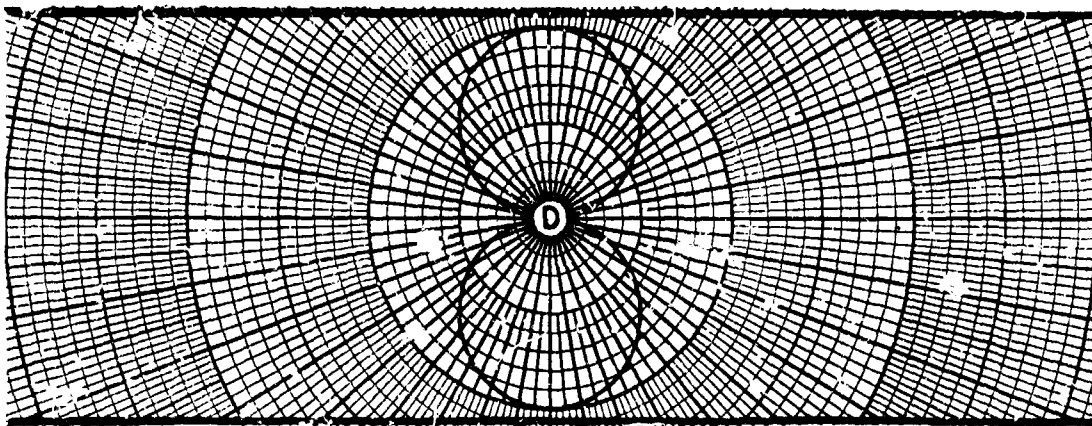


Figure 3.7a Detector between Parallel, Infinite Walls;  $E = 1.00$

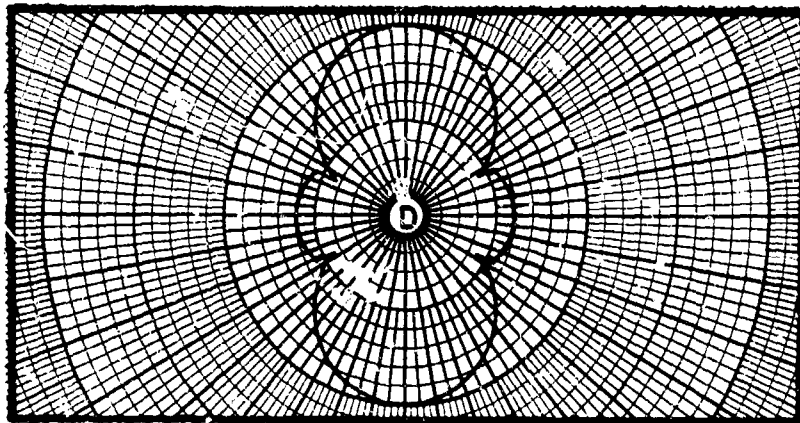


Figure 3.7b Detector in a Rectangular Building;  $E = \frac{1 + e}{1 + e^2}$

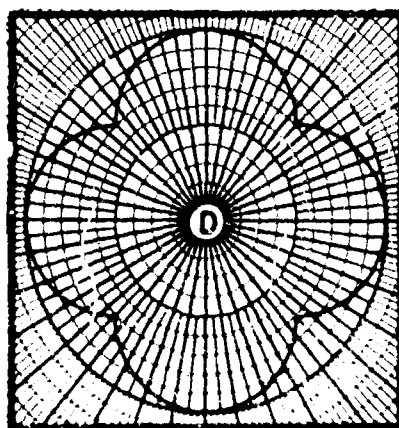


Figure 3.7c Detector in a Square Building;  $E = \sqrt{2}$

FIGURE 3.7 Wall-scatter Radiation as a Function of Building Shape

expression:

$$E = \frac{1 + e}{1 + e^2} \quad (3.6)$$

gives the factor "E", termed the "Shape Factor", as a function of the eccentricity, e, of the building, by which the wall-scattered radiation determined for the parallel wall case ( $G_s$  from chart 5) may be converted to the case of a rectangular building. The Shape Factor, E, for a detector location centered in a square building is  $\sqrt{2}$  and for a detector location centered in a circular building is  $0.5 \pi$ .

The total Geometry Factor for ground contribution,  $G_g$ , is the sum of the non-wall-scattered directional responses multiplied by the fraction of the radiation emergent from the wall which has not been wall-scattered, and the wall-scattered directional responses multiplied by both the fraction of the emergent radiation which has been wall scattered and the Shape Factor. In standard notation,

$$G_g = (G_d + G_e) \times (1 - S_w) + (G_s + G_g) \times S_w \times E \quad (3.7)$$

### 3.4.3 BARRIER SHIELDING

#### 3.4.3.1 Mass

The determination of the effects of mass is the basic element of barrier shielding and the most important part of a correct analysis. The effectiveness of mass is determined in part by the atomic number of the shielding element and the energy of the incident radiation. The system of analysis is based on the shielding properties of a single substance, water, and the energy spectrum of fission products 1.12 hours after detonation. The shielding properties of water closely approximate the net shielding obtained from common building construction materials such as concrete, which are composed of elements with generally low atomic numbers. The energy spectrum of fallout varies considerably with time after the detonation due to different half-lives of the radioactive isotopes.

The spectrum of fission products at 1.12 hours after detonation is either representative or a conservative approximation for the spectrum at other times after detonation. The radioactivity of fallout is principally from fission products. Unfissioned bomb fragments and neutron induced radioactivity in soil are a minor source of the radioactivity of fallout.

The effectiveness of mass is also dependent on the amount of mass that the radiation must pass through to get to a detector and the angle of incidence of the radiation with an air-wall interface. Attenuation of radiation between the contaminated field and the walls of the structure due to the mass of air is included with the barrier reduction factor for exterior walls. The actual mass of the wall is measured in pounds per square foot of barrier surface. Increased effectiveness of a barrier in reducing radiation not normal to its surface is accounted for in the derivation of the barrier reduction factors for specific applications. Thus, different curves are used for barriers in different orientations from the detector. Such curves are prepared for use for floors below the detector, case 1, chart 1; for floors above the detector, case 3, chart 1; and for exterior walls, chart 2.

#### 3.4.3.2 Height Above Contaminated Plane

The radiation received by an unshielded detector varies with its height above a uniformly contaminated plane. The effects of distance away from the emitting source and scattering and absorption in the air are given in Figure 4.6 Reduction Factors for Height and Slant Radius. The value read from Figure 4.6 is all the radiation received by the unshielded detector at a specific height in comparison to the radiation received by THE STANDARD, 1.0.

The effect of height above the contaminated plane is incorporated into the barrier reduction factor for the exterior wall. This corrects all ground contribution for height by the variation of only a single factor. Roof contribution is not affected by height as the sources of the radiation are in contact with the structure surface.

#### 3.4.3.3 Collimation and Angle of Incidence

The effectiveness of a barrier is partially dependent upon the angle at which the radiation strikes the surface. The same barrier is less effective in reducing radiation which strikes normal to its surface than it is for radiation which strikes at some other angle. The radiation striking a vertical barrier at a height 3 feet above a uniformly contaminated field of indefinite extent has the angular distribution of THE STANDARD, as shown in Figure 3.2. In elevation, the bulk of this radiation is almost parallel to the ground surface. At higher elevations, radiation strikes the wall surface from an average direction considerably below the horizontal.

See Figures 3.8a and 3.8b. The effectiveness of the mass is increased with increasing departure from the normal of the incident radiation. Thus, the effectiveness of the mass in the exterior wall increases with height of the wall

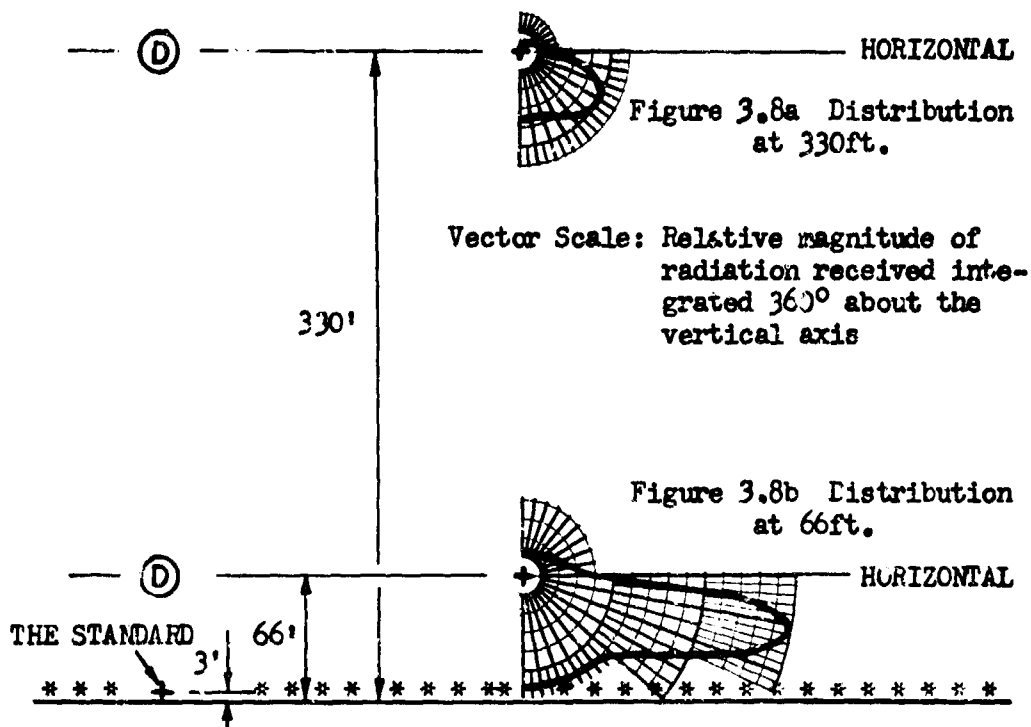


Figure 3.8 Variation in Directional Distribution of Radiation with Height

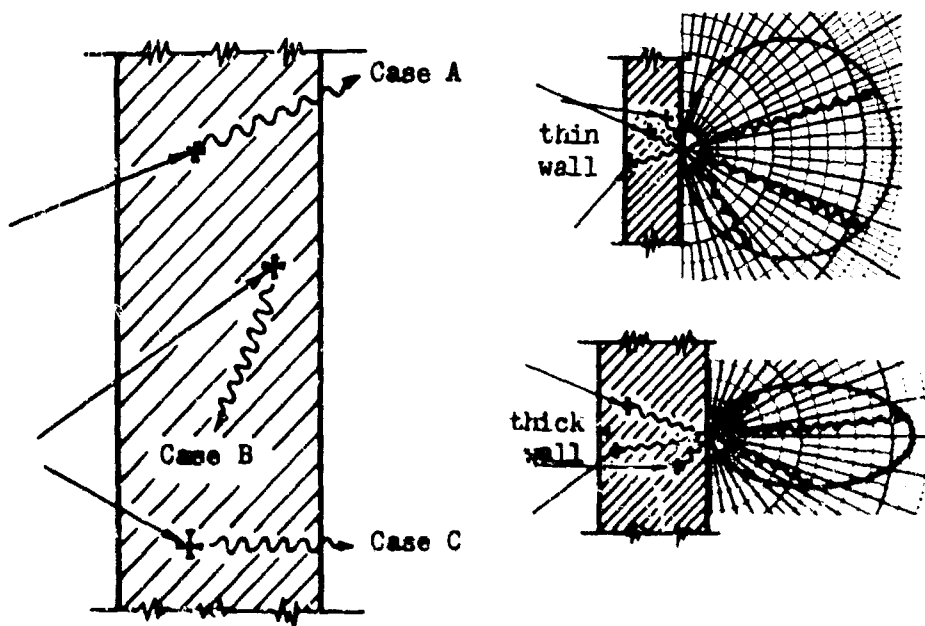


Figure 3.9 Collimation of Wall-scatter Radiation



above the contaminated plane. This relationship is included in chart 2, Reduction Factors for Ground Contribution through Vertical wall barriers.

Since with increasing height, the bulk of the radiation received by a point above a contaminated plane has an increasing tendency to come from the same direction (from vertically below the detector), the air is said to have a collimating effect on the radiation. Collimation is one effect of any mass upon incident radiation. When radiation is scattered within mass it may travel in any direction, Figure 3.9. That which has been scattered the least will retain the most energy and will tend to emerge from the mass approximately in its original direction of travel, case A. Radiation which has been scattered more has an increased chance of being further scattered or absorbed within the barrier, case B. When the direction of travel after scattering is essentially normal to the surface, the radiation has the least chance of absorption or further scattering and the greatest chance of emerging from the barrier, case C. This effect is such that with increasing mass of the barrier, the scattered radiation has a greater tendency to emerge normal to the surface of the barrier. As the fraction of the emergent radiation which has been scattered also increases with the amount of mass, the collimation, the tendency of the radiation to travel in parallel paths, becomes very pronounced with high mass thicknesses.

The barriers of a structure, walls, roof, and floors, collimate the radiation with a resulting increased effectiveness of the barriers. Interior partitions forming barriers to ground contribution are an exception in that the radiation emerging from the exterior walls has been collimated and thereby has the tendency to travel horizontally. Thus the interior partition barrier reduction factor for ground contribution does not include increased effectiveness for collimation, the factor used is that for a vertical barrier at a height of 3 feet above the contaminated plane, the height of THE STANDARD. If the radiation has been collimated by passing through a horizontal barrier such as a floor or roof with a resulting tendency to travel vertically, the effectiveness of the interior partition as a barrier is increased. This increase is provided for roof contribution by the use of a separate curve for the interior partition barrier reduction factor, Chart 11.

As noted in paragraph 3.4.3.1, separate curves are used for the barrier reduction factors for floors above and below the detector elevation. The use of two curves for floors is principally due to the greater energy, and thus greater penetrating ability, of the ground direct radiation.

### 3.5 FUNCTIONAL EXPRESSIONS

#### 3.5.1 DEFINITION

The variables which determine the amount of shielding afforded a point within a structure have a complex relation to their parameters. As can be noted in Chapter 4, charts, these relationships can be expressed by highly complex formulas. These formulas are not used in the system of shielding analysis however, but are replaced by charts which graphically express the relation of the various terms to their parameters. Functional expressions are used to show that relationship does exist between a term and the independent variables which determine it, without expressing the precise nature of the relation.

An example of functional notation may be given with the expression:

$$Z = X^2 Y$$

where Z is the dependent variable, and X and Y are the independent variables whose values determine the magnitude of Z. The functional notation for this relationship could be written:

$$Z = f(X, Y) : \text{where } Z \text{ is a function of } X \text{ and } Y, \text{ or}$$

$$Z(X, Y) : \text{where } Z \text{ is a function of } X \text{ and } Y.$$

Note that functional notation does not express the exact relationship, but only that a relationship exists. Thus, the term  $Z(X, Y)$  could also represent:

$$Z = \frac{X}{Y}, Z = X^Y, Z = XY, \text{ etc.}$$

#### 3.5.2 FUNCTIONAL NOTATION OF BASIC TERMS

The system of shielding analysis employs many factors, which are determined by the physical properties of the structure under analysis. Preceding paragraphs have presented and defined these terms. The normal functional notation used when they are incorporated in functional expressions is given below:

$B_e(X_e, H_d)$  - Exterior wall barrier reduction factor, a function of exterior wall mass thickness,  $X_e$ , and detector height above contaminated plane,  $H_d$ .  $H_d$  is taken as 3' for basement cases.

$B_f(X_f)$  - Barrier reduction factor for floor immediately beneath detector, a function of floor mass thickness,  $X_f$ .

- $B_1(X_1, 3')$  - Interior partition barrier reduction factor for ground contribution, a function of interior partition mass thickness,  $X_1$ , and a height of 3'.
- $B_1^i(X_1)$  - Interior partition barrier reduction factor for roof contribution, a function of interior partition mass thickness,  $X_1$ .
- $B_0^i(X_0^i)$  - Barrier Reduction factor for ground contribution for floor immediately over the detector, a function of the mass thickness of that floor,  $X_0^i$ .
- $E_{ws}(X_0, \omega_s)$  - Reduced barrier reduction factor for wall-scattered radiation with mutual shielding, a function of exterior wall mass thickness,  $X_0$ , and the solid angle fraction for the finite field of contamination seen at midstory height,  $\omega_s$ .
- $E(e)$  - Shape factor for wall-scattered radiation, a function of the eccentricity ratio,  $e$ .
- $G_a(\omega)$  - Directional response for skyshine radiation, a function of solid angle fraction,  $\omega$ .
- $G_d(\omega, H_d)$  - Directional response for ground direct radiation, a function of solid angle fraction,  $\omega$ , and detector height above the contaminated field,  $H_d$ .
- $G_s(\omega)$  - Directional response for wall-scattered radiation, a function of solid angle fraction,  $\omega$ .
- $S_w(X_0)$  - Fraction of emergent radiation scattered in wall barrier, a function of exterior wall mass thickness,  $X_0$ .

### 3.5.3 ROOF CONTRIBUTION

The basic functional expression for roof contribution combines factors for barrier reduction and geometry effects.

$$R_f = C_0(\omega, X_0) \quad (3.8)$$

where  $R_f$  - Reduction Factor for roof contribution,

$C_0(\omega, X_0)$  - Contribution of radiation lying on roof and skyshine through the roof, a function of the solid angle fraction determined by the contributing roof area and the total overhead mass thickness,  $X_0$ , of mass in horizontal planes between the detector and the contamination.

When the contribution of a portion of the roof must come through an interior partition, the net contribution of that portion of the roof must be multiplied by an interior partition barrier reduction factor for roof contribution.

$$R_T = \text{net } C_0 \times B_I^r(X_1) \quad (3.9)$$

where  $B_I^r(X_1)$  is the interior partition barrier reduction factor for roof contribution, and which by derivation, takes into account the increased effectiveness of the interior partition due to collimation by the overhead mass.

Equations 3.8 and 3.9 are the general expressions for roof contribution. The determination of "net  $C_0$ " and other applications of these expressions are illustrated in Chapters 5 and 6.

#### 3.5.4 GROUND CONTRIBUTION

The basic functional expression for ground contribution combines barrier and geometry reduction factors:

$$C_g = B \times G_g \quad (3.10a)$$

where  $C_g$  = Reduction factor for ground contribution.

$B$  = Product of the applicable Barrier reduction factors.

$G_g$  = Geometry reduction factor for ground contribution.

This functional expression may be expanded to include the actual factors used in the determination:

$$C_g = B_0(X_0, H) \times E_1(X_1, 3') \times \left\{ \left[ G_d(\omega_L, H_d) + G_s(\omega_u) \right] \times \left[ 1 - S_w(X_0) \right] + \left[ G_s(\omega_L) + G_s(\omega_u) \right] \times S_w(X_0) \times E(\phi) \right\} \quad (3.10b)$$

The above expression is the contribution through the wall on the story of the detector of a rectangular, aperture-less structure symmetrical about the detector.

Contributions through the exterior walls of adjacent stories, through walls with windows, or through walls of varying mass thickness are computed using variations of equation 3.10b in which all the appropriate barrier reduction factors are included, net values are substituted for the directional response values shown, and provision for different type walls is made by repeating the expressions with the appropriate barrier and geometry reduction factors and then weighting the resultant expressions in accordance with the portion of the total structure they represent.

Azimuthal sectors, in which the angle in plan subtended by the specific wall for which the expression is written is made a fraction of the building by dividing by 360°, are usually used for this weighting procedure.

As the basic functional expression for ground contribution, equation 3.10 or variations of this formula, are written for a situation which is the same all around the detector, the non-uniform case must be calculated by using several functional expressions, each weighted by an appropriate azimuthal sector. Thus, a general expression for ground contribution may be written:

$$C_g = A_{z1}(B \times G_g)_1 + A_{z2}(B \times G_g)_2 + A_{z3}(B \times G_g)_3 + \text{etc.} \quad (3.11)$$

### 3.6 SUMMARY

The Detailed Procedure introduced by this Chapter, and the Simplified, Approximate Procedure to be derived from it demand skill in application. Both systems require visualization of a structure and the manner in which a complex facility may be divided into simple components suitable for analysis.

The ability of the analyst to make this visualization and his working ability with the tools of analysis make the systems practical. The working ability is achieved only by practice, however the material presented in this section are the necessary tools.

### 3.7 REFERENCES

L. V. Spencer, Structure Shielding Against Fallout Radiation from Nuclear Weapons, National Bureau of Standards Monograph 42, June 1962.

OCDM Engineering Manual, Design and Review of Structures for Protection from Fallout Gamma Radiation, Office of Civil and Defense Mobilization, July 1, 1961, (Interim Edition).

Samuel Glasstone, editor, The Effects of Nuclear Weapons, U.S. Atomic Energy Commission, April 1962.

### 3.8 NOTATION

The following is the basic list of symbols for shielding analysis, exclusive of those used only in the Simplified Procedure:

A.....Area (sf).

$A_p$ .....Fraction of contributing wall area occupied by apertures.

$A_z$ .....Azimuthal sector.  
 $A_{za}$ .....Azimuthal sector of apertures.  
 $B$ .....Barrier reduction factor for plane isotropic source of radiation.  
 $B_e$ .....Barrier reduction factor for exterior wall construction.  
 $B_f$ .....Barrier reduction factor for floor below the detector.  
 $B_i$ .....Barrier reduction factor for interior wall construction.  
 $B'_i$ .....Barrier reduction factor for overhead (roof) contribution through an interior partition.  
 $B'_c$ .....Barrier reduction factor for ground contribution through the floor over the detector.  
 $B_{ws}$ .....Barrier reduction factor for wall-scattered radiation (mutual shielding case only).  
 $C_g$ .....Reduction factor accounting for combined barrier and geometry shielding effects; ground contribution.  
 $C_o$ .....Reduction factor accounting for combined barrier and geometry shielding effects; overhead (roof) contribution including skyshine through the roof.  
 $e$ .....Eccentricity ratio =  $W/L$ .  
 $E$ .....Shape correction factor for wall-scattered radiation.  
 $F_e$ .....Effective fetch (ft.).  
 $G$ .....Geometry reduction factor.  
 $G_a$ .....Directional response for skyshine radiation.  
 $G_d$ .....Directional response for ground direct radiation.  
 $G_g$ .....Geometry reduction factor for ground contribution.  
 $G_s$ .....Directional response for wall-scattered radiation.  
 $H$ .....Height above contaminated plane (ft.).  
 $H_d$ .....Height of detector above contaminated plane (ft.).

$L$ .....Length of structure (ft.).  
 $n$ .....Normality ratio =  $2Z/L$ .  
 $P_a$ .....Perimeter ratio of apertures.  
 $P_f$ .....Protection factor.  
 $P_r$ .....Perimeter ratio.  
 $P_s$ .....Barrier reduction factor for point isotropic source.  
 $R_f$ .....Reduction factor.  
 $S_w$ .....Fraction of emergent radiation scattered in wall barrier.  
 $(1-S_w)$ .....Fraction of emergent radiation not scattered in wall barrier.  
 $U$ .....Unit weight of barrier (pcf).  
 $W$ .....Width of structure (ft.).  
 $W_c$ .....Width of finite contaminated strip (ft.).  
 $X_e$ .....Mass thickness of exterior walls (psf).  
 $X_f$ .....Mass thickness of floor construction (psf).  
 $X_i$ .....Mass thickness of interior walls (psf).  
 $X_o$ .....Total overhead mass thickness (psf).  
 $X_d$ .....Mass thickness of floor over the detector (psf).  
 $X_r$ .....Mass thickness of roof construction (psf).  
 $Z$ .....Perpendicular distance between horizontal plane and detector (ft.).  
 $\omega$  (omega).Solid angle fraction.  
 $\omega_s$  (omega).Solid angle fraction subtended by limited field for a point at midwall height in mutual shielding cases.  
 $\omega_1, \omega_2$  etc..Solid angle fraction in first, second, etc. leg of passageway or shaft.

## CHAPTER 4

### DETAILED PROCEDURE - CHARTS

#### 4.1 INTRODUCTION

##### 4.1.1 OBJECTIVE

The design and analysis of structures for protection from fallout gamma radiation requires the determination of the degree of protection given by both mass and geometry effects. The reduction due to these two effects is found by relating a given structure to standard configurations for which the reduction factor is known. Once the reduction factors for the standard configurations are known, the result for the given structure can be determined. This chapter will present the basic charts used for determination of the reduction factor for standard configurations and a discussion of the background and derivation of these charts. Thus a basis is provided for estimating the degree of accuracy and applicability of the charts for actual structural situations.

##### 4.1.2 BACKGROUND

The fully-developed portion of the theory of gamma ray diffusion and penetration applies only to media that are homogeneous and infinite. Practical shielding applications, however, require consideration of boundaries and irregularities. The basic study in this field has indicated that economy of effort and increase in accuracy can be achieved, if boundary problems are approached by applying corrections to a solution for an infinite homogeneous medium. Such an approach is suggested by the fact that in many circumstances the boundary effects are relatively small. Further, the approach allows application of the extensive results for infinite homogeneous media that have been calculated by exact methods. The method that is employed to correct for the presence of boundaries is modification of infinite medium results through an appropriate schematization.

Most theoretical data derives from study of a simple case in which the medium has no irregularities (an infinite homogeneous medium). The source may be a plane in the medium or concentrated at a point. In these situations, detector response as a function of distance from the source can be calculated to a precision of a few percent. These calculations have internal consistency and reliability, and usually represent a good approximation of reduction in intensity due to actual slab barriers. It is convenient to select a standard based on these calculations and to use ratios between actual detector response due to radiation from a particular



wall, for example, and this standard. The resulting ratios express nearly all the special characteristics of the configuration. Paragraphs 3.3 and 3.4 present a discussion of the analytical procedure and the use of barrier and geometry factors based upon these infinite medium calculations.

#### 4.1.3 BASIC ASSUMPTIONS AND VARIABLES

Fallout is assumed to uniformly cover all horizontal surfaces and the horizontal projection of sloping surfaces. This forms the primary source of radiation which travels to the detector, wherever it may be. A "Standard Unprotected Position," THE STANDARD as defined in paragraph 3.2.2, is chosen as a detector location three feet above a hypothetical infinite plane source of the same character as the fallout on the ground. Ground roughness is avoided by making the source plane ideally smooth. This choice of reference detector location:

- a. Gives an extreme, but not unrealistic estimate of the dose rate to which the centroid of the body is exposed in an open contaminated field.
- b. When given the spectrum and strength of the gamma rays emitted per unit area, permits the reference dose rate to be calculated to about 2 - 3% accuracy.
- c. Allows ground roughness to be considered as a separate variable.

The "protection factor,"  $P_f$ , is defined as the ratio of THE STANDARD detector response,  $D_0$ , to the protected response,  $D$ :

$$P_f = D_0 / D$$

The reciprocal of  $P_f$ , the REDUCTION FACTOR, is used in structure fallout analysis. The ratio  $D/D_0$  will be used in place of reduction factor for the development of the charts in this chapter.

In addition to selecting the location of the detector at a height of 3 feet above an infinite contaminated plane, the spectrum of fallout radiation used is that existing at 1.12 hrs. after fission. Figure 4.1 shows the relative intensities of different spectral components at several times after fission. The height of each box is proportional to the energy content of gamma rays in the energy interval, and the central line indicates an energy assumed for all photons in the interval for purposes of calculation. The lines do not correspond to spectral energies actually present. The total intensity is unity for each spectrum. Once the spectrum is selected for THE STANDARD, the relative effectiveness of various

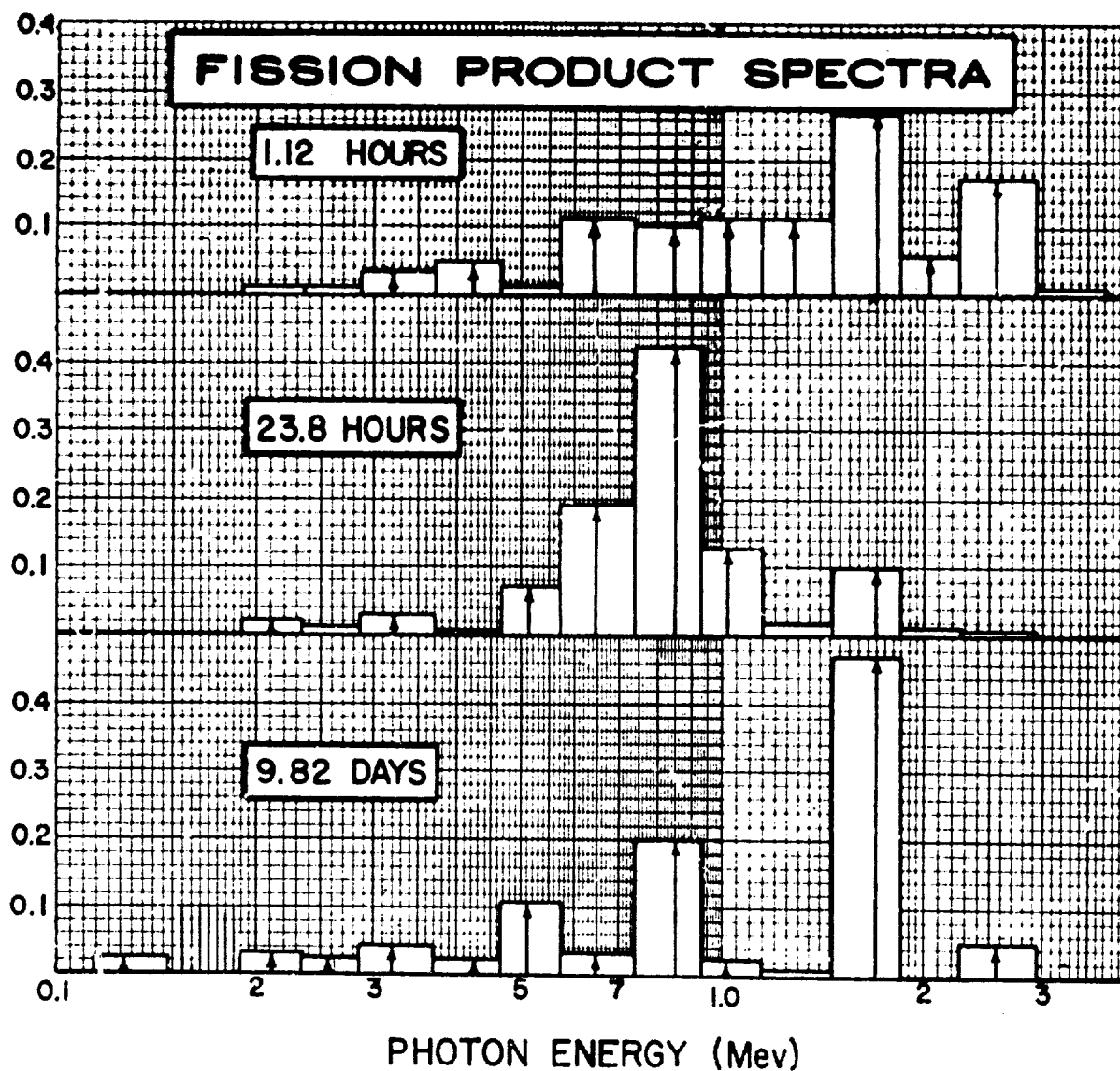


Figure 4.1 The Relative Intensities of Different Spectral Components at Several Times after Fission

configurations can be determined.

In review, the basic assumptions introduced thus far are: uniform distribution of contamination; spectrum at 1.12 hours after fission; and location of THE STANDARD.

The shielding provided by a barrier depends upon many variables, among which are:

- (a) the weight per unit area of the barrier
- (b) the type of barrier material
- (c) the gamma ray spectrum
- (d) the directional distribution of the radiation striking the barrier.

The type and thickness of the barrier can be treated as one variable due to a fortunate circumstance: nearly all important construction materials have atomic numbers sufficiently low that attenuation is due primarily to scattering interactions, which are independent of the energy states occupied by the electrons. Thus, the attenuation produced by a barrier depends almost completely upon how many electrons it puts in the path of the gamma rays per unit area; this is simply the product of the number of electrons per unit volume times the thickness of the barrier.

The effectiveness of barrier shielding is measured by a parameter,  $X$ , which is proportional to the barrier thickness,  $t$ , and to  $u \times \frac{Z}{A}$  where  $u$  is the density and  $\frac{Z}{A}$  is the ratio of atomic charge to atomic mass number, averaged over the constituent elements of the barrier.  $X$  is defined by the expression:

$$X = 2\left(\frac{Z}{A}\right) u t \quad (4.1)$$

The factor of two is introduced because  $\left(\frac{Z}{A}\right)$  is nearly 0.5 for such important construction materials as brick and concrete, so that  $2\left(\frac{Z}{A}\right) \approx 1$  for those materials. If  $2\left(\frac{Z}{A}\right) \approx 1$  is treated as a dimensionless proportionality constant, then  $X$  can be measured in pounds per square foot, with  $u$  and  $t$  measured in  $\text{lbs/ft}^3$  and feet respectively. As  $X$  is nearly equal to the weight per unit area or "mass thickness" it is termed the effective mass thickness. Table 4.1 gives values for  $2\frac{Z}{A}$  for a number of common materials together with the density of the solid material. Table 4.2 lists values of mass thickness for common building materials.

Table 4.1 Values of  $2 Z/A$  and  $U$

<u>Material</u>	<u><math>2 \times Z/A</math></u>	<u><math>U</math>, Density in pcf</u>
Water	1.11	62.4
Wood	1.06	34.0 (average)
Air	1.0	0.076
Brick	1.0	115
Concrete	1.0	144
Soil (depending on water content)	1.00 - 1.02	100 (average)
Steel	0.931	480
Lead	0.791	710

Barrier shielding factors,  $B$ , are functions of the effective mass thickness, i.e.,  $B = B(X)$ . Use of the concept of effective mass thickness makes it possible to perform calculations even when barriers are composed of several layers of different materials: the effective mass thicknesses of the different layers are added to obtain the total mass thickness.

The other basic variables upon which the detector response depends are presented in Chapter 3 and are listed here:

a. Geometry shielding (paragraph 3.4.2) based on solid angle fraction (paragraph 3.4.2.2) which is used to determine directional responses and overhead contributions, as modified by the fraction of radiation scattered in the wall and the influence of the shape of the area (paragraph 3.4.2.3).

b. Barrier shielding (paragraph 3.4.3) based primarily upon mass of the barrier (paragraph 3.4.3.1), as modified by height above contaminated plane (paragraph 3.4.3.2), collimation, and angle of incidence (paragraph 3.4.3.3).

## 4.2 DERIVATION OF CHARTS

### 4.2.1 MEASUREMENT AND DISTRIBUTION OF RADIATION

The actual measurement of radiation traversing a given region requires a suitable detector as a probe. The detector should be small so that all parts of it are exposed to the same radiation

Table 4.2 Mass Thickness of Common Building Materials.

INDIVIDUAL BUILDING MATERIALS			
Item	Thickness	Weight Psf	Component
Adobe.....	Inches 12	116	Wall
Asbestos board.....	3/4	1.7	Do.
Asbestos, corrugated.....	4	4	Roof, wall
Asbestos shingles.....	3/4	1.8	Do.
Asphalt roofing, 3-ply ready.....	.....	1	Roof
Asphalt roofing, 4-ply & gravel.....	.....	5.5	Do.
Asphalt roofing, 5-ply & gravel.....	.....	6.2	Do.
Asphalt shingles.....	.....	2.3	Do.
Brick.....	4	39±1	Wall
Do.....	8	79±10	Do.
Do.....	12 1/4	115±15	Do.
Do.....	17	154±20	Do.
Clay tile shingles.....	.....	15±5	Roof
Clay tile, structural.....	4	18	Wall
Concr. block, hollow.....	4	30±4	Do.
Do.....	8	55±5	Do.
Do.....	12	85±10	Do.
Concrete, reinforced.....	1	12 1/2	Do.
Do.....	12	144-150	Do.
Fiber board.....	1/2	0.3	Wall
Fiber sheathing.....	1/2	0.9	Do.
Gypsum block.....	2	9.5±1.5	Do.
Do.....	4	12.5±2.5	Do.
Gypsum board.....	1/2	2.1	Wall, ceiling
Gypsum, sheathing.....	1/2	2.0	Wall
Marble facing.....	2	26	Do.
Plaster, directly applied.....	3/4	5	Wall, ceiling
Plaster on fiber lath.....	1/2	5.0	Do.
Plaster on gypsum lath.....	1/2	6.0	Do.
Plaster on metal lath.....	3/4	6.0	Do.
Plaster on wood lath.....	3/4	5.0	Do.
Plaster, solid.....	2	20	Wall
Do.....	4	30	Do.
Plywood, finish.....	3/4	1.0	Do.
Do.....	1/2	1.5	Ceiling
Plywood, sheathing.....	3/4	1.1	Wall, roof
Slate.....	3/4	7.3	Roof
Steel, corrugated, 20 ga.....	.....	2	Roof, wall
Steel panel, 18 ga.....	.....	3.26	Wall, roof
Stone.....	12	130	Wall
Stone, cast, facing.....	2	24	Do.
Stucco, metal lath.....	3/4	9.0	Do.
Stucco, wood lath.....	3/4	8.0	Do.
Terra cotta facing.....	1	5.4	Do.
Wood block, flooring.....	3	10	Floor
Wood finish flooring.....	2 1/2	2.5	Do.
Wood sheathing.....	3/4	2.5	Floor, roof
Wood shingles.....	.....	2.5	Roof
Wood shingles 6 1/2 in. to weather.....	.....	1.1	Wall
Wood siding, 8 in. level.....	.....	1.5	Do.
Wood siding, 6 in. drop.....	.....	2.5	Do.

COMPOSITE MATERIALS			
Item	Thickness	Weight Psf	Component
Brick and structural clay tile.....	4	60	Wall
Ceramic tile on mortar bed.....	3/4	11	Do.
Do.....	2	23	Floor
Concrete, reinforced ribbed slabs (see section on components).....	.....	.....	Do.
Marble or terrazzo on concrete fill.....	4	50	Do.
Plaster, hollow wall with steel studs.....	4	22	Wall
Plaster on suspended metal lath.....	.....	10	Ceiling
Wood finish floor on wood sleeper.....	3/4	.....	Do.
Lightweight concrete fill.....	4	23	Floor

DOORS AND GLASS			
Item	Thickness	Weight Psf	Component
Door, wood exterior, standard 3 ft-0 in. x 6 ft-8 in. solid core flush panel.....	Inches 1 3/4	4.5	Small buildings
Door, wood interior, standard 2 ft-6 in. x 6 ft-8 in. hollow core.....	1 3/4	1.9	Do.
Door, glass exterior, solid core.....	1 3/4	4.0	Do.
Door, glass exterior, aluminum edge, standard 3 ft-0 in. x 7 ft-0 in.....	1 3/4	5.1	Large buildings
Door, glass exterior standard, 3 ft-0 in. x 7 ft-0 in.....	3/4	11.0	Do.
Glass, double strength.....	3/4	1.6	Small buildings
Glass, plate.....	3/4	3.5	Large buildings

flux and it does not appreciably disturb the flux distribution. The response measured by such a detector is due to photons which traverse the detector material. These photons may be characterized by the direction of their trajectory at the time they enter the detector. Direction is identified by means of polar coordinates which are measured with respect to an arbitrary polar axis through the center of the detector and a reference half-plane terminating along the polar axis (as shown in Figure 4.2). The vertical angle,  $\theta$  (theta), and the azimuth,  $\phi$  (phi), are measured to a line extending out from the center of the detector parallel to the trajectory but opposite the direction of travel of the photon. The angle which this line forms with the polar axis is  $\theta$ , while  $\phi$  is the angle between the reference plane and the plane terminating along the polar axis which contains this line. Any direction of incidence is uniquely specified by values for these two direction coordinates.

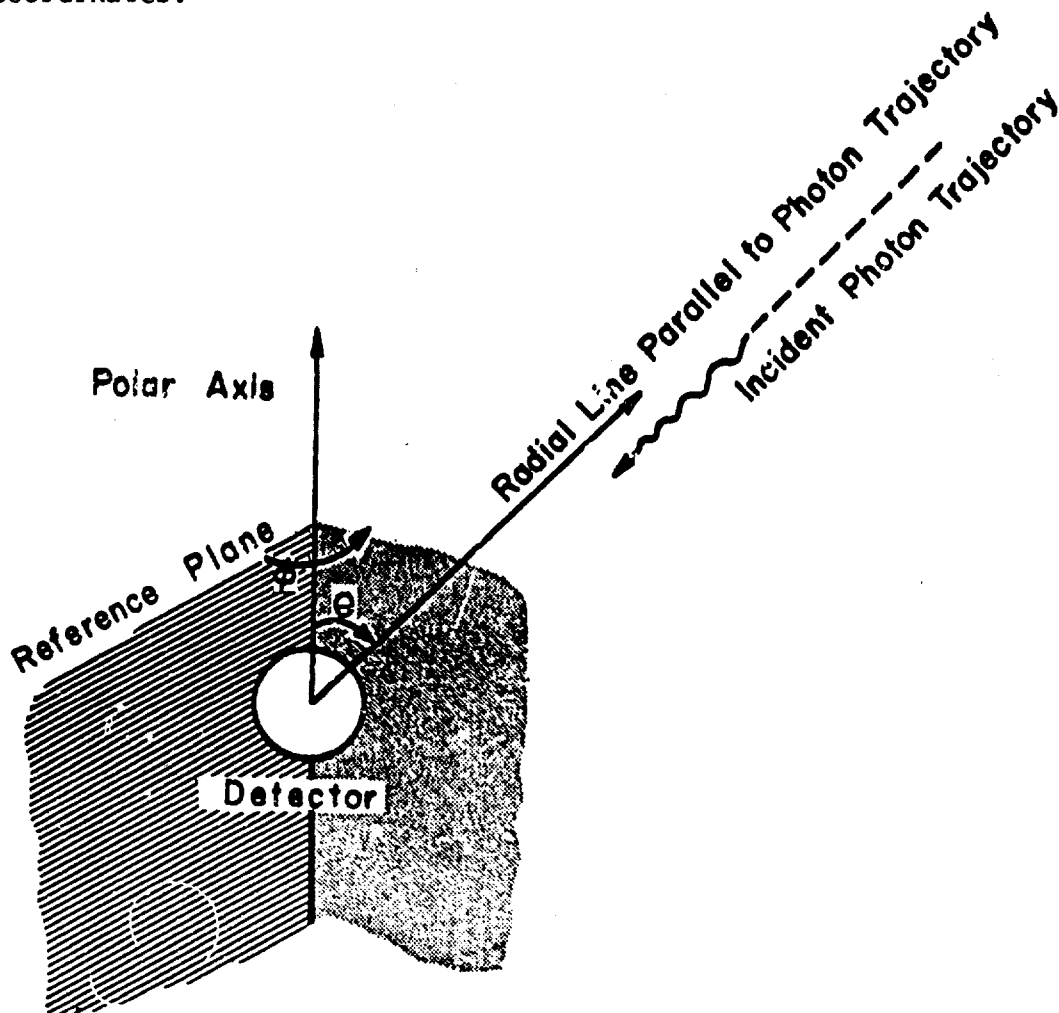


Figure 4.2 Coordinate System for Detector Position

Note that the coordinate pairs  $(\theta, \phi)$  may also identify a unique point on a sphere of unit radius centered at the detector. The coordinate pairs can thereby be referred to as a direction or a point on a unit sphere.

The total detector response,  $D = D(\theta, \phi)$ , is made up of contributions from all directions.  $D(\theta, \phi) \sin \theta d\theta d\phi$  is the portion of the total detector response due to gamma rays with incident trajectories between  $\theta$  and  $\theta + d\theta$ , and between  $\phi$  and  $\phi + d\phi$ . The total response from all directions is expressed by the integral:

$$\begin{aligned} D &= \int_0^\pi \sin \theta d\theta \int_0^{2\pi} d\phi D(\theta, \phi) \\ &= \int_{-1}^1 d(\cos \theta) \int_0^{2\pi} d\phi D(\theta, \phi) \end{aligned} \quad (4.2)$$

The function  $D(\theta, \phi)$  is referred to as the detector DOSE ANGULAR (or DIRECTIONAL) DISTRIBUTION.

When there is symmetry about the polar axis due to the nature of the radiation field,  $D(\theta, \phi)$  does not depend upon  $\phi$ , and the function  $D(\theta, \phi)$  can be written in the form  $D(\theta, \phi) = \left( \frac{1}{2\pi} \right) D(\theta)$ . Equation 4.2 becomes:

$$D = \int_0^\pi D(\theta) \sin \theta d\theta \quad (4.3)$$

This expression gives the total response of a detector at a given position in space due to a given source of radiation. The only stated requirement is that the resulting distribution of radiation intensity received by the detector must be symmetrical about the polar axis. The use of Equation 4.3 will be presented with the derivation of the height chart (paragraph 4.2.3).

#### 4.2.2 HEIGHT CHART

Consider an infinite isotropic, plane source of fallout radiation imbedded in an infinite, homogeneous medium, Figure 4.3, with the distance of the detector from the source plane represented by  $d$ . The distances may be referred to alternatively in terms of  $X$ , (lbs/ft<sup>2</sup>) the effective mass thickness between source and the

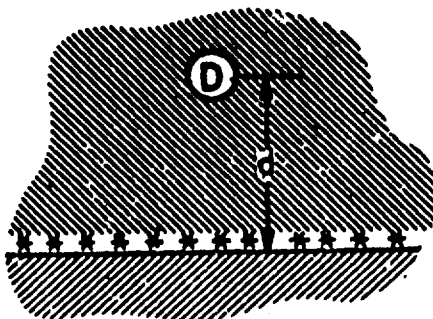


Figure 4.3 Isotropic Detector, Plane Isotropic Source

detector. If the medium is air (at  $20^{\circ}$ , 76 cm Hg), the relation between  $d$  and  $X$  is:

$$d/X = 13.3 \text{ ft of air/psf.}$$

At distance  $d$  from the source plane, the radiation produces a dose angular distribution which is referred to as  $\mathcal{L}(d, \cos\theta)$ , where  $\theta$  is the vertical angle measured from the perpendicular through detector to the source plane and which forms the polar axis. The scale of  $\mathcal{L}(d, \cos\theta)$  is so fixed that an isotropic detector which registers  $D_0$  roentgens/per hour three feet above the source will register  $dD_0 \mathcal{L}(d, \cos\theta) \sin\theta d\theta$  roentgens/per hour due to gamma rays striking the detector between  $\theta$  and  $\theta + d\theta$ , or:

$$\int_{-1}^1 d(\cos\theta) \mathcal{L}(3; \cos\theta) = 1 \quad (4.4)$$

Equation 4.4 is equivalent to equation 4.3 with the function  $D(\theta)$  written as  $\mathcal{L}(3; \cos\theta)$ .

The function  $\mathcal{L}(d, \cos\theta)$  is the same as the dose angular distribution discussed in paragraph 4.2.1 with an additional variable for height,  $d$ . It represents the dose rate received by a collimated detector oriented at an angle  $\theta$  with respect to the vertical. A sketch of this function  $r = \mathcal{L}'(d, \theta)$  as a function of  $\theta$  is shown in Figure 4.4, which shows the angular variation on a polar plot where the radial vector  $r$ , is the incremental dose integrated  $360^{\circ}$  about the polar axis. The radial scale in Figure 4.5 is logarithmic so that the variations of dose rate with  $\theta$  are much more severe than shown, as may be seen in Figure 3.2 and 3.8. The notation  $r = \mathcal{L}'(d, \theta)$  is used to distinguish between the dose angular distribution in terms of  $d$  and  $\theta$  and that in terms of  $d$  and  $\cos \theta$ , written above as  $\mathcal{L}(d, \cos\theta)$ .



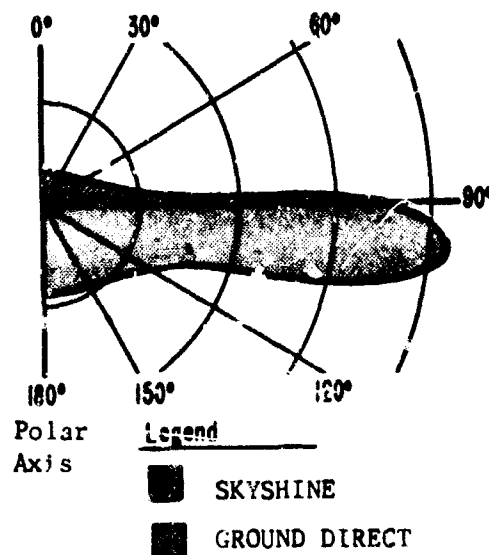


Figure 4.4 Directional Distribution (Plane Case)

Figure 4.5 illustrates the appearance and behavior of  $Q(d, \cos\theta)$ . These curves represent actual results for penetration by a 1.12 hr fission spectrum in an infinite medium of water, which is sufficiently similar to air in regards to interaction probabilities that these curves have been scaled to correspond to feet of air. Various features of these curves should be noted: near the source plane (low  $d$ ),  $Q(d, \cos\theta)$  is proportional to  $(\cos\theta)^{-1}$  for angles approaching but less than  $\pi/2$  (i.e.,  $\cos\theta \rightarrow 0$ ). This results in large values for directions nearly parallel to the source plane, an important feature of the radiation from this type of source. With increasing height above the source plane, the directional distribution is increasingly weighted toward  $\theta = 180^\circ$  (i.e., vertically downward). With great height above the source plane (high  $d$ ), the initially dominant oblique components are preferentially removed.

The total response of the detector at a height  $d$  above the contaminated plane is, from equation 4.4:

$$L(d) = \int_0^\pi Q(d, \theta) \sin\theta d\theta \quad (4.5a)$$

$$L(d) = \int_{-1}^1 Q(d, \cos\theta) d(\cos\theta) \quad (4.5b)$$

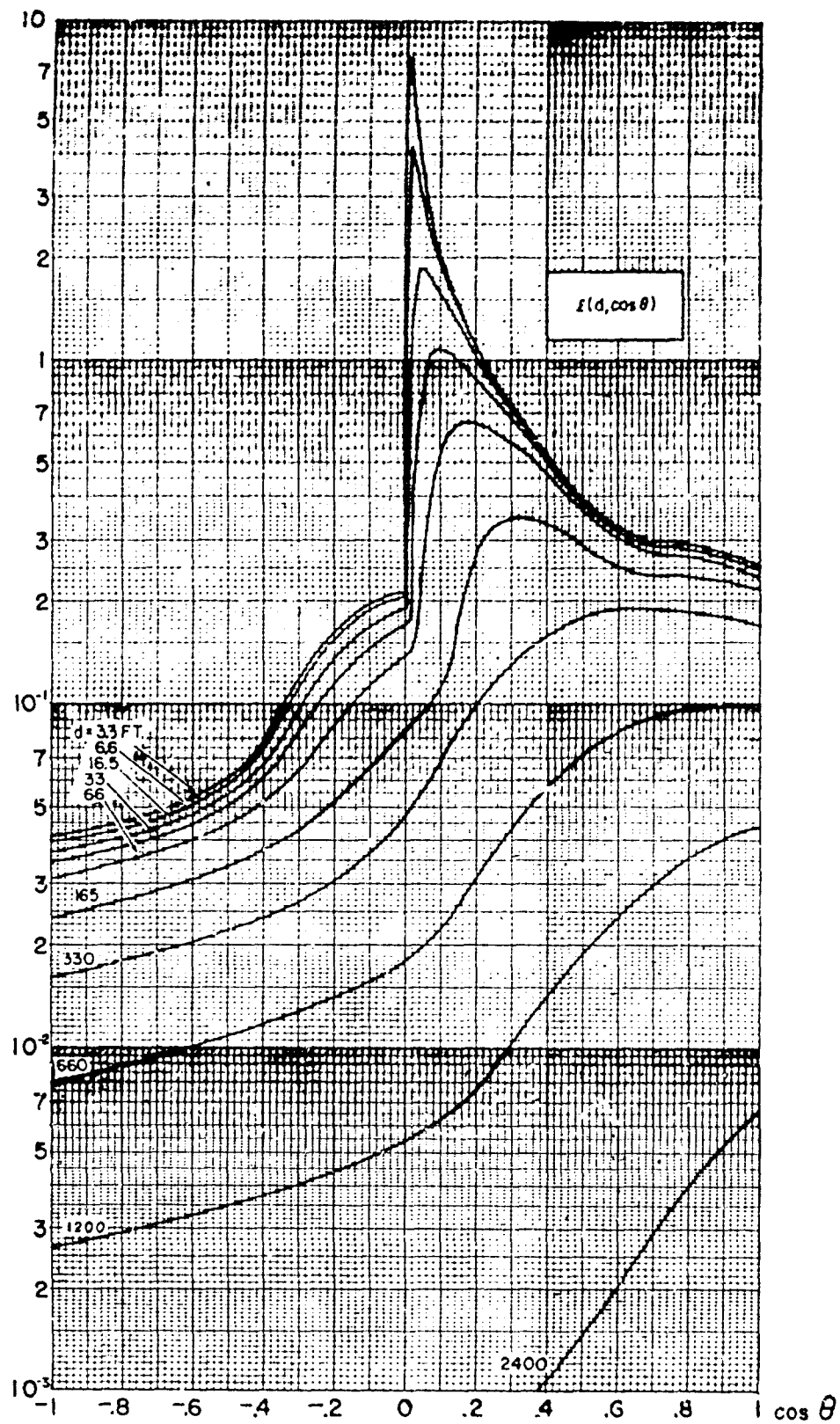


Figure 4.5 Dose angular distributions  $L(d, \cos \theta)$  for an idealized plane fallout source, at different heights in air ( $d$ ) above the source.

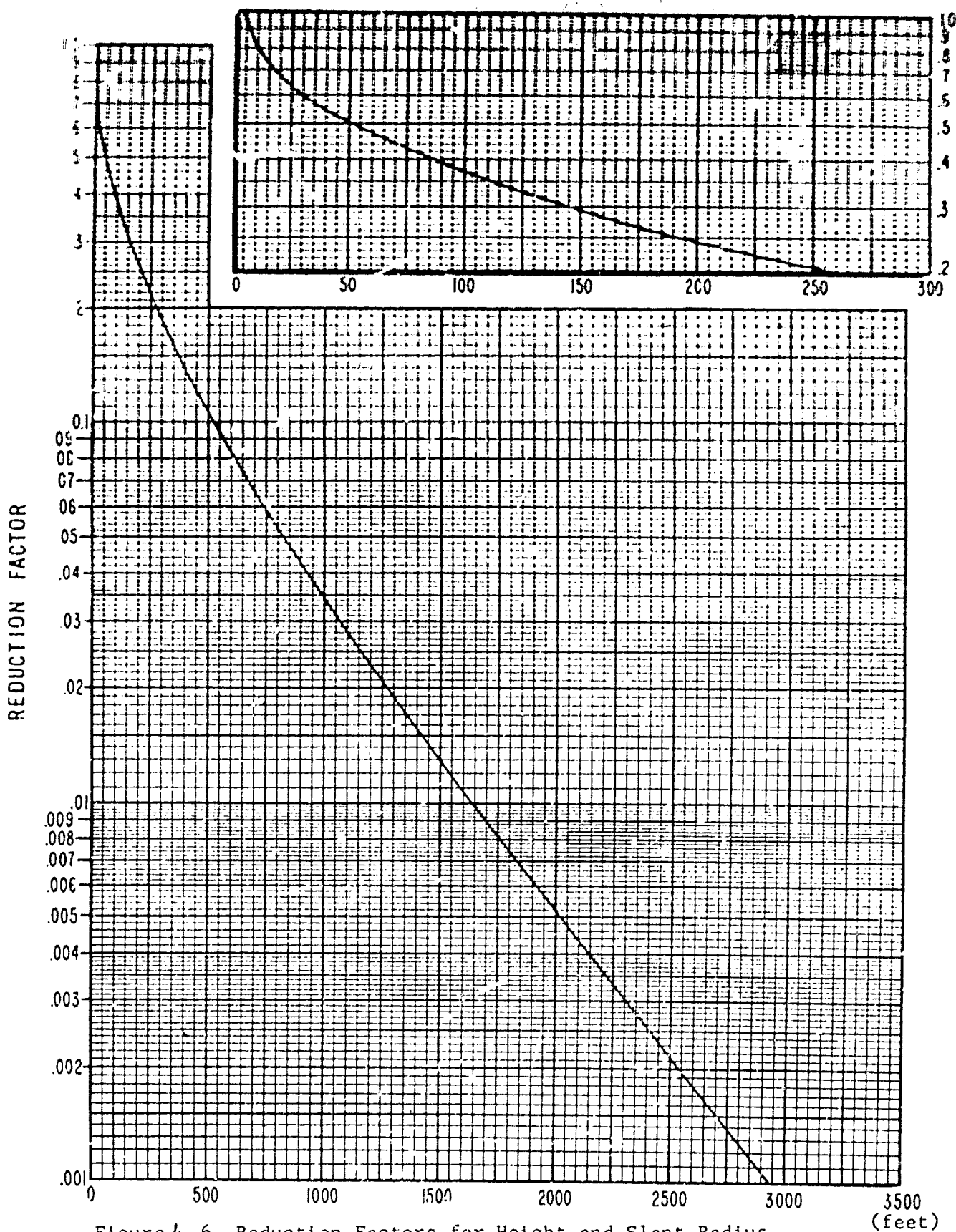


Figure 4.6 Reduction Factors for Height and Slant Radius

Equation 4.5b expresses the response in terms of the variable  $\cos\theta$  while the first equation expresses the response in terms of the angle  $\theta$ . In view of the normalization of THE STANDARD at  $d=3$  feet,  $L(d)$  is simply the total detector response at a distance  $d$  (in air) from an infinite plane, isotropic source, divided by the detector response at 3 feet in air from the same source. Note that the detector response includes radiation that has travelled past the detector and has been back scattered as well as radiation that has been back scattered from the semi-infinite space below the detector. These responses are inherent in the determination of the dose angular distribution function.

Figure 4.6 shows the variation in reduction factor  $L(d)$  with height above the contaminated plane. The curve goes to a value of one at a height of 3 feet, corresponding to THE STANDARD POSITION.

Figure 4.6 can also be employed for the configuration shown in Figure 4.7 below, where  $X$  may be considered equivalent to distance in feet.

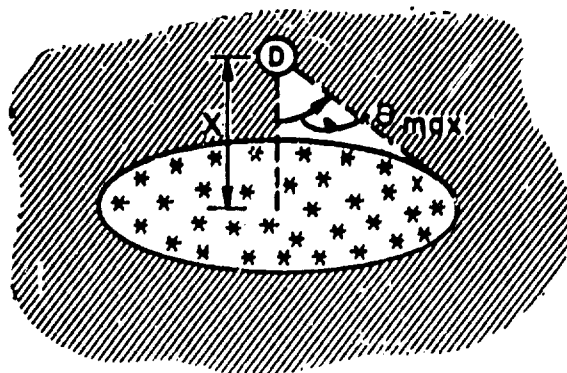


Figure 4.7 Isotropic Detector, Isotropic Circular Source

The response from the circular area of contamination can be considered as that from the entire plane minus that from beyond the circular region:

$$D = L(X) - L(X / \cos\theta_{max})$$

where  $(X/\cos\theta_{max})$  is the slant radius of the circular region. In addition, Figure 4.7 can be used for the response of a detector from an infinite plane of contamination with a cleared circular area. If in Figure 4.7 the shaded area is considered as fallout and the asterisks the cleared area, the response is

$$D = L(X / \cos\theta_{max})$$

where again  $(X/\cos\theta_{max})$  is the slant radius of the cleared area. The function  $L$  is obtained directly from Figure 4.6.

#### 4.2.3 CHART 1 - $B_F(X_F)$ CURVE

If the relation between height in air and mass thickness is introduced, THE DETECTOR response for the configuration shown in Figure 4.3 can be written in the form:

$$L(X) = \int_{-1}^1 \rho(X, \cos \theta) d(\cos \theta)$$

$L(X)$  is the same function as  $L(d)$  except that distance from the source is expressed in terms of the effective mass thickness.

The curve of  $B_F(X_F)$ , Chart 1 shows the variation in the reduction factor expressed by  $L(X)$  above as a function of mass thickness. The curve goes to a value of one at a mass thickness corresponding to a mass thickness of 3 feet of air. Note that the configuration shown with Chart 1,  $B_F(X_F)$  does not correspond to the configuration used in its derivation (Figure 4.3) but rather to a situation which may arise in the analysis of the shielding characteristics of a structure. This will be typical of all the charts to be discussed, since it is necessary to apply the results of standard configurations to actual situations.

#### 4.2.4 CHART 1, $B'_O(X'_O)$ CURVE

The effectiveness of a barrier to radiation that has been back scattered can be found by employing the configuration shown in Figure 4.8.

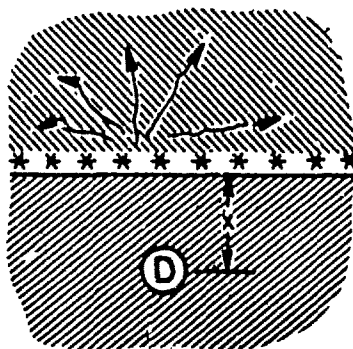


Figure 4.8 Isotropic Detector, Source Isotropic only in Directions Pointing away From the Detector

The configuration sketched in Figure 4.8 shows a plane source emitting gamma rays isotropically in an upward direction into an infinite homogeneous medium. The detector is below the source plane, separated from it by an effective mass thickness  $X$ . Radiation can be backscattered to the detector, giving a response which can be calculated. A normalization to unity at  $X = 0$  is

is convenient for use as a reduction factor in the applications, so that the resulting detector response is the ratio of the response at a given mass thickness to that at a mass thickness of zero. Chart 1,  $B'_0(X'_0)$  gives the response function for this configuration. Again note that the sketch given with this curve does not correspond exactly to the configuration used in the derivation of the curve, but rather to the situation for which the curve is used.  $B'_0(X'_0)$  Chart 1 is used to determine the barrier reduction factor for radiation from the walls of the story above the detector as reduced by the intermediate floor.

#### 4.2.5 CHART 10

Calculations apply to the response of a detector with a conical collimator of solid angle.

##### Case 1

This calculation applies to the reduction factor in a vertical shaft below a horizontal circular aperture, such as a skylight, which is covered with radioactive material. This value of  $R_F = 1$  for  $\omega = 1$  corresponds to a detector which is separate from the source by a barrier thickness equivalent to three feet of air (i.e. 0.23 PSF). This curve includes a skyshine contribution.

##### Case 2

This calculation applies to the reduction factor in a horizontal passageway leading from a vertical circular aperture. The value of  $R_F = \frac{1}{2}$  for  $\omega = 1$  corresponds to a detector which is located in the vertical plane of the aperture and thus receives radiation from a semi-infinite plane.

##### Case 3

This calculation applies to the reduction factor on a vertical shaft below a horizontal circular aperture which is not covered with radioactive material. The value of  $R_F = 0.1$  for  $\omega = 1$  corresponds to a detector which is located in the horizontal plane and thus measures the total skyshine contribution.

#### 4.2.6 CHART 2, $B_e(X_eH)$ ; CHART 1, $B_1(X_1)$

The effectiveness of a vertical barrier can be determined using the configuration shown in Figure 4.10. Fallout radiation is assumed to be uniformly distributed over a semi-infinite half

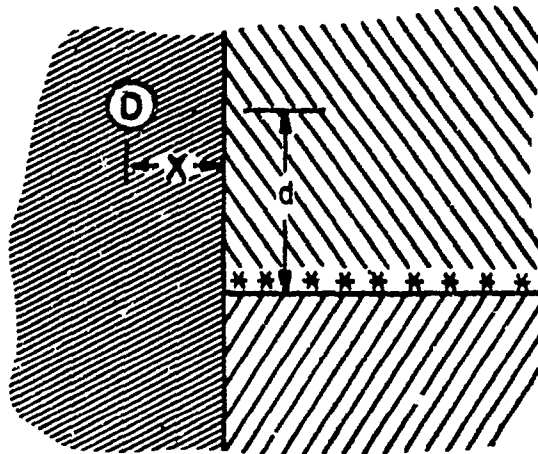


Figure 4.10 Isotropic Detector and Plane Isotropic Source: The Radiation Field at Height  $d$  Above the Primary Source is taken as a New Source at a Penetration  $X$  to the Right of the Detector.

plane. The detector is located a distance  $d$  above the contaminated plane and separated from the outside medium by a material with mass thickness  $X$ . It is required to find the total response of the detector in this position. The angular distribution of radiation incident on a vertical wall is assumed to be the same as if the wall were not present. This distribution corresponds to a distance  $d$  in air from an infinite plane source in a homogeneous medium, but with directions referred to a polar axis perpendicular to the vertical wall (i.e. parallel to the source plane). The spectrum incident on the wall is assumed to be that generated by the primary source on the ground; an integral over all oblique angles of incidence is made; and the radiation at each angle is weighted according to theoretical data on oblique penetration. The result approximates the total detector response at a height  $d$

above the source plane and with a mass thickness  $X$  of barrier material between detector and external barrier surface. Errors in this calculation arise from inaccuracies in the angular distribution, changes in the incident spectrum as the scattered radiation component becomes more important, and incorrect correlation of spectrum with direction. In general, this function represents the vertical wall barrier reduction factor accurately for  $d$  small, compared with a mean free path of the source radiation, in air, i.e.  $d \ll 1000$  feet.

Chart 2 presents the results obtained from this configuration with some modifications. The results shown in Chart 2 are normalized to the detector response at THE STANDARD detector location of 3 feet; and the results are for a configuration which is symmetrical about a vertical line through the detector. The zero mass thickness line thus corresponds to the height chart given in Figure 4.6. The results for a height of 3 feet are shown in Chart 1,  $B_1(X_1)$  curve. The results in Chart 2 give the barrier reduction factors relative to THE STANDARD and include the effects of air attenuation, collimation in air, and the effect of mass of the vertical barrier. The effect of collimation is included by accounting for the directional distribution on the vertical wall as discussed above.

#### 4.2.7 CHART 1 $B_1'(X_1)$ CURVE

In the analysis of roof contributions, it is necessary to account for the effect of interior partitions. Since the radiation emerging from overhead mass has been collimated by that mass, it is necessary to include an effect of this collimation in the barrier reduction factor for the interior partition. This collimation causes the interior partition (or vertical barrier) to be more effective than it would be if the radiation were not collimated.

The barrier reduction factor for this case is found by considering the ratio of the total radiation impinging upon the vertical barrier to that emerging from it.

Figure 4.10 shows the typical standard configuration. The radiation which the detector receives relative to THE STANDARD is given by the curves of Chart 2. For the roof contribution however, the overhead mass thickness is replaced by the equivalent distance  $d$  obtained from the relation:

$$d/X = 13.3$$

discussed previously. This results in:

$$B_1(X_1, d=13.3X_0)$$



which is the response accounting for the effects of mass, attenuation, and collimation and is the ratio of the total radiation at the detector to that at THE STANDARD. However, the required barrier reduction factor is the ratio of the radiation inside to that outside. This latter value is simply the height chart, or to continue to use Chart 2, the value of  $B_1$  at zero mass thickness and a height  $d=13.3X_0$ , that is

$$B_1(0, 13.3X_0)$$

The ratio below, gives the total radiation inside to that outside: and is the effective barrier reduction factor for a vertical barrier for roof contributions:

$$B_1' = \frac{B_1(X_1, 13.3X_0)}{B_1(0, 13.3X_0)}$$

If this ratio is calculated for a range of  $X_0$  and  $X_1$  values it is found that for  $X_0 = 50$  psf the curves for various values of  $X_1$  are nearly vertical, suggesting that beyond 50 psf an increase in  $X_0$  does not significantly effect  $B_1$ . It is also determined that most of the change in this ratio occurs as  $X_0$  varies from 0 to 12 psf. As a result, one curve, for  $X_0=50$  psf, is adequate to account for the ratio given above and this value

$$B_1'(X_1) = B_1(X_1, 660)/B_1(0, 660)$$

is shown in Chart 1 ( $B_1'(X_1)$  Curve).

This barrier factor is used in the analysis of roof contributions as discussed in chapter 5.

#### 4.2.8 CHART 3

Chart 3 presents curves of the solid angle fraction for the ranges of parameters indicated. These curves give the solid angle fraction subtended at a point detector by a rectangular area, and were calculated from the expression:

$$\omega = (2/\pi) \tan^{-1} \left[ \frac{e}{n(n^2 + e^2 + 1)^{1/2}} \right]$$

#### 4.2.9 CHART 4

The introduction of the solid angle fraction permits evaluation of the effect of finite fields of contamination. Figure 4.11 shows a circular area of fallout having its center directly

opposite a detector and separated by a layer of material of mass thickness  $X$ . The solid angle fraction defined by the circular area is  $= 1 - \cos \theta_{\max}$

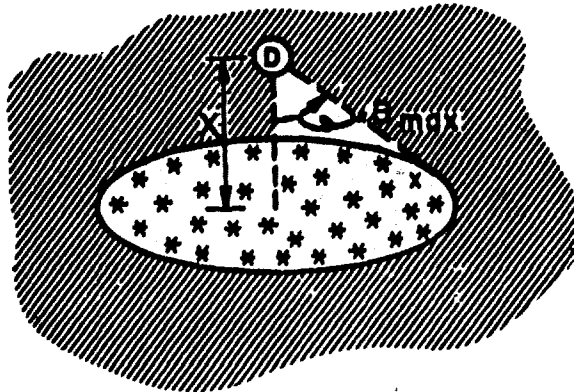


Figure 4.11 Isotropic Detector, Isotropic Circular Source

Chart 4 presents curves of the ratio of the response due to the circular disk to THE STANDARD. The barrier is assumed to be uniformly distributed between source and detector. The detector therefore receives both skyshine and radiation backscattered from the medium below.

Note that the figure shown on Chart 4 is not exactly the configuration used in deriving the curves of the chart, but is shown for convenience as typical of a roof configuration.

The line  $\omega = 1$  of Chart 4 is the height chart, Figure 4.6 since a solid angle fraction  $= 1.0$  corresponds to an infinite plane of contamination. Since radiation backscattered from the medium below is considered in the derivation of this chart, the limiting value at  $\omega = 1$  and  $d = 3$  feet of air is 1.0. As the mass thickness of 3 feet of air (0.23 psf) cannot be distinguished from the 0 psf line they can be considered identical for practical purposes.

#### 4.2.10 CHART 9

In cases where the source has finite dimensions the barrier reduction factor for the infinite source (Chart 2) is replaced by a reduced barrier reduction factor for wall-scattered radiation.

This is discussed in greater detail in chapter 5.

The barrier reduction factor shown in Chart 9 for wall-scattered radiation from finite sources is based on unpublished calculations, in which the dose rate behind a wall due to unscattered incident radiation from semicircular sources was calculated. These semicircles were concentric about a point at the base of the wall directly below the detector position on the wall. The results are a function of the wall thickness and the solid angle fraction  $\omega$  subtended by the source. The effect of height on the barrier reduction factor is not important for the usual range of solid angle fractions. The extension of the curves of Chart 9 shown in this text beyond those given in the prior text, was carried out using the 3 feet line of Chart 2.

#### 4.2.11 CHART 5

##### 4.2.11.1 Skyshine Case $G_a$

In the analysis of structures, it is necessary to account for the amount of radiation passing through the vertical walls above the detector plane. This is shown in the sketch with the  $G_a$  curve on Chart 5.

The curve for  $G_a$  is obtained by considering the configuration shown in Figure 4.12. It is required to find the amount of skyshine radiation reaching the detector

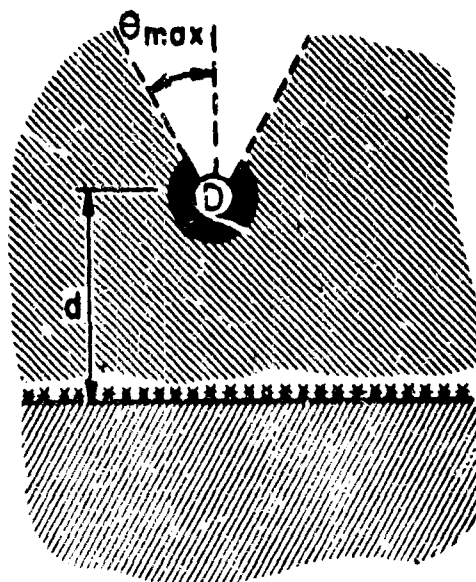


Figure 4.12 Conical Detector Pointed away from a Plane Isotropic Source

through the upper cone defined by  $\theta_{\max}$ . This angle is defined by a circular area whose solid angle fraction is

$$\omega = 1 - \cos \theta_{\max}$$

The basic data for skyshine radiation is obtained from the directional distribution functions given in Figure 4.5.

The curve for  $G_s$  was obtained for the case where  $d=0$ , that is, detector located on the source plane. The variation of skyshine with height is not significant and is neglected. The value of 0.1 at  $\omega=0$  is the ratio of the skyshine radiation to the total radiation received at a detector at a height of 3 feet. Although the curve was derived at  $d=0$ , it is used at all heights and is normalized with radiation received by THE STANDARD.

In addition to the skyshine radiation reaching the detector directly, an additional effect is included in the  $G_a$  curve of Chart 5; namely, a correction term to account for the radiation reflected from the ceiling. This correction factor is made a function of the upper solid angle in order to account for the relative location of the ceiling.

#### 4.2.11.2 Scattered Case $G_s$

The factor,  $G_s$ , attempts to account for scattering of radiation by the walls. As only limited information is available on the wall scattering effect, it is necessary to approximate the distribution of scattered radiation. Since skyshine is basically scattered radiation it is used to obtain the  $G_s$  curve shown in Chart 5.

It is assumed that scattered radiation is symmetrical with respect to a horizontal plane through the detector position, so that the normalization is to 0.5 at  $\omega=0$ .

Again it should be noted that the solid angle fractions utilized in the derivation of both the  $G_s$  and  $G_a$  curves were obtained from circular areas, and that both curves are assumed to be insensitive to height.

#### 4.2.12 CHART 6

Ground direct radiation as a function of solid angle fraction is obtained directly from the directional distribution curves given in Figure 4.5. The only distinction between this case and that

of skyshine is that the region of interest is below the detector plane. Chart 6 presents curves of the ratio of ground direct radiation as a function of the indicated solid angle fraction at a given height, to that of the total radiation at that height. These curves were obtained directly from Figure 4.5 and by using circular solid angle fractions.

The value of  $G_d$  at 3 feet and  $\omega=0$  is 0.9 indicating that at the standard position, 0.9 of the total radiation is ground direct while 0.1 is skyshine. The vertical line at  $\omega=0$  shows that, as the detector is moved away from the plane of contamination, the fraction of the total radiation which is ground direct decreases slightly; while it is assumed, in Chart 5, that the skyshine fraction of the total radiation does not vary.

Chart 6 includes only the effect of geometry and does not account for attenuation of radiation due to height. This effect is included in the barrier reduction factor which is obtained from Chart 2.

#### 4.2.13 CHART 7

The method of analysis discussed in the Chapter 3 stated that the system distinguishes between radiation which has been scattered in the walls and that which has not. The fraction of the emergent radiation that has been scattered in a wall barrier is shown as a function of mass thickness in Chart 7. If the mass thickness is zero, no radiation is scattered, while if the mass thickness is infinite all the radiation is scattered.

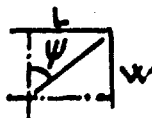
Chart 7 was derived for the configuration shown in Figure 4.9. The ratio of the scattered radiation to the total radiation was determined as a function of the mass thickness separating the detector and source. As in all calculations performed to obtain the basic charts, the source was assumed to be that of gamma rays emitted by fission products 1.12 hrs after fission.

The sketch shown with this chart is not the configuration employed to obtain the curve but rather is illustrative of the use of Chart 7 in actual applications.

#### 4.2.14 CHART 8

The charts discussed above have, within the framework of the assumptions, been obtained from schematization of certain basic configurations. Chart 8 however, is a curve introduced to account approximately for the shape of the building in the scatter geometry contribution. It is obtained by assuming that the response at a

detector due to wall-scattered radiation is proportional to  $\sin \psi$  when  $\psi$  is the angle shown below. This is an approximation



of the directional distribution of radiation emerging from the wall. The wall-scattered response in a rectangular building is the sum of the responses from the walls, so that the shape factor:

$$E = \sin \psi + \sin \left( \frac{\pi}{2} - \psi \right) = \sin \psi + \cos \psi$$

$$= (1 + \tan \psi) / \sec \psi = (1 + e) / (1 + e^2)^{1/2}$$

where  $e = (W/L)$

This factor is plotted in Chart 8 and is utilized with the wall-scattered component as discussed in Chapter 3.

#### 4.3 SUMMARY

The discussion of the charts and their derivation in Section 4.2 has been based upon the material presented in Reference 1. Table 4.3 presents the correspondence between the charts presented in this chapter and contained in the OCDM Manual "Design and Review of Structures for Protection from Fallout Gamma Radiation" to the data and discussions contained in Reference 1.

Columns (2), (3), and (4) of Table 4.3 present the notation, figure and discussion references from Reference 1 which have been utilized to obtain the charts indicated in Column (1). The relation between the referenced figures and the charts is indicated in the comments, Column (5).

Table 4.3 can be used with the text of this chapter to obtain a more detailed discussion of the charts, including the mathematical derivations.

#### 4.4 REFERENCE

1. Spencer, L. V., Structure Shielding Against Fallout Radiation From Nuclear Weapons, National Bureau of Standards Monograph 42, 1 June 1952

TABLE 4.3 CORRESPONDENCE OF CHARTS TO DATA OF REF. 1

(1) CHART NUMBER	(2) FUNCTIONAL NOTATION	(3) FIGURE REFS.	(4) PAGE REFS.	(5) COMMENTS
1. Case 1, and Height Chart	$L(X)$ , Eq. (27.2) $L(d)$	28.1(a) and 28.2(a), (b)	P29, 28(1)	
1 Case 2; also CHART 11	See Chart 2			
1 Case 3	$S'(X)$ , Eq. (27.4)	28.1(c) and 28.4	P29, 28(3)	
2	$W(X,d)$ , Eq. (27.7)	28.1(e) and 28.7	P30, 28(6)	Normalize to 3 feet; 2 x Fig (28.7), Symmetry
3	$\tau(\epsilon, \eta)$ , Eq. (41.3)	41.2(a)	P68, 41	
4	$L_c(X, \omega)$ , Eq. (27.8)	28.8(a) and 28.9, 28.18	P30, 28(7)	
5 $G_a$	$S_a(d, \omega)$ , Eq. (27.13)	28.13(b) and 28.15, 28.3	P53, 28(12)	$d=0$ , Normalize from Fig 28.3 to 0.1; Albedo correc- tion applied, $A_c$
5 $G_s$	Same as above	- - - -	- - - -	The results for $G_a$ and $G_s$ were obtained from the following expressions $G_s = 0.5[1 - (\text{Fig 28.15})]$ , $d=0$ $G_a = (1/5)G_s[1 + A_c]$ , $d=0$ $A_c = 5[0.1 - 0.2G_s]$ $A_c$ is a function of $\omega$
6	$\frac{\int_0^{H-\omega} L(H, \cos\theta) d(\cos\theta)}{\int_{-1}^1 L(H, \cos\theta) d(\cos\theta)}$			When $H=3'$ , ratio becomes $\frac{\int_0^{H-\omega} L(3, \cos\theta) d(\cos\theta)}{\int_{-1}^1 L(3, \cos\theta) d(\cos\theta)}$ in view of normalization at 3'
7	$P(X)$ , Eq. (27.5) and $P(S)(X)$ , Eq. (27.6), Eq. (28.1)	28.1(d) and 28.6	P30, 28(4), (5)	$S_w(X) = \frac{P(S)(X)}{P(S)(X) + P(S)(X)}$
8	N/A	N/A	N/A	$E = (1+e)/(1+e^2)^{1/2}$
9	N/A	N/A	N/A	Special calculation See Text, par. 4.2.10

#### 4.5 CHARTS FOR THE DETAILED PROCEDURE

- Chart 1. Barrier Shielding Effects (Plane Sources)
- Chart 2. Wall Barrier Shielding Effects for Various Heights
- Chart 3. Solid Angle Fraction
- Chart 4. Reduction Factors for Combined Shielding Effects,  
Roof Contribution,  $C_o$
- Chart 5. Directional Responses, Ground Contribution,  $G_g$  and  $G_a$
- Chart 6. Directional Responses for Various Heights,  $G_d$
- Chart 7. Fraction of Emergent Radiation Scattered in Wall  
Barrier,  $S_w$
- Chart 8. Shape Factor for Wall-scattered Radiation,  $E$
- Chart 9. Barrier Reduction Factors for Wall-scattered Radiation  
for Limited Strip of Contamination
- Chart 10. Reduction factor for passageways and shafts



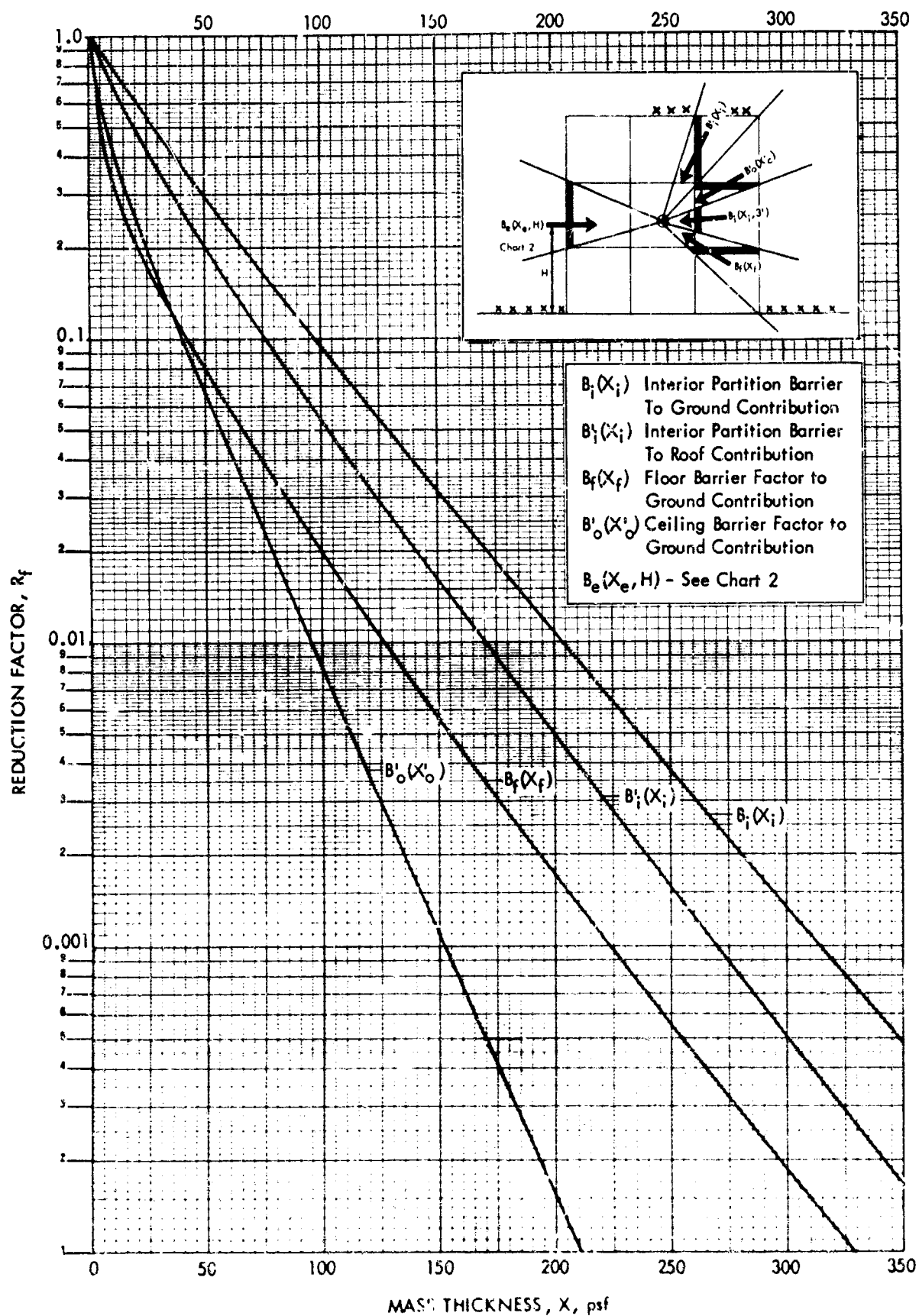


Chart 1. BARRIER SHIELDING EFFECTS, PLANE ISOTROPIC SOURCES.

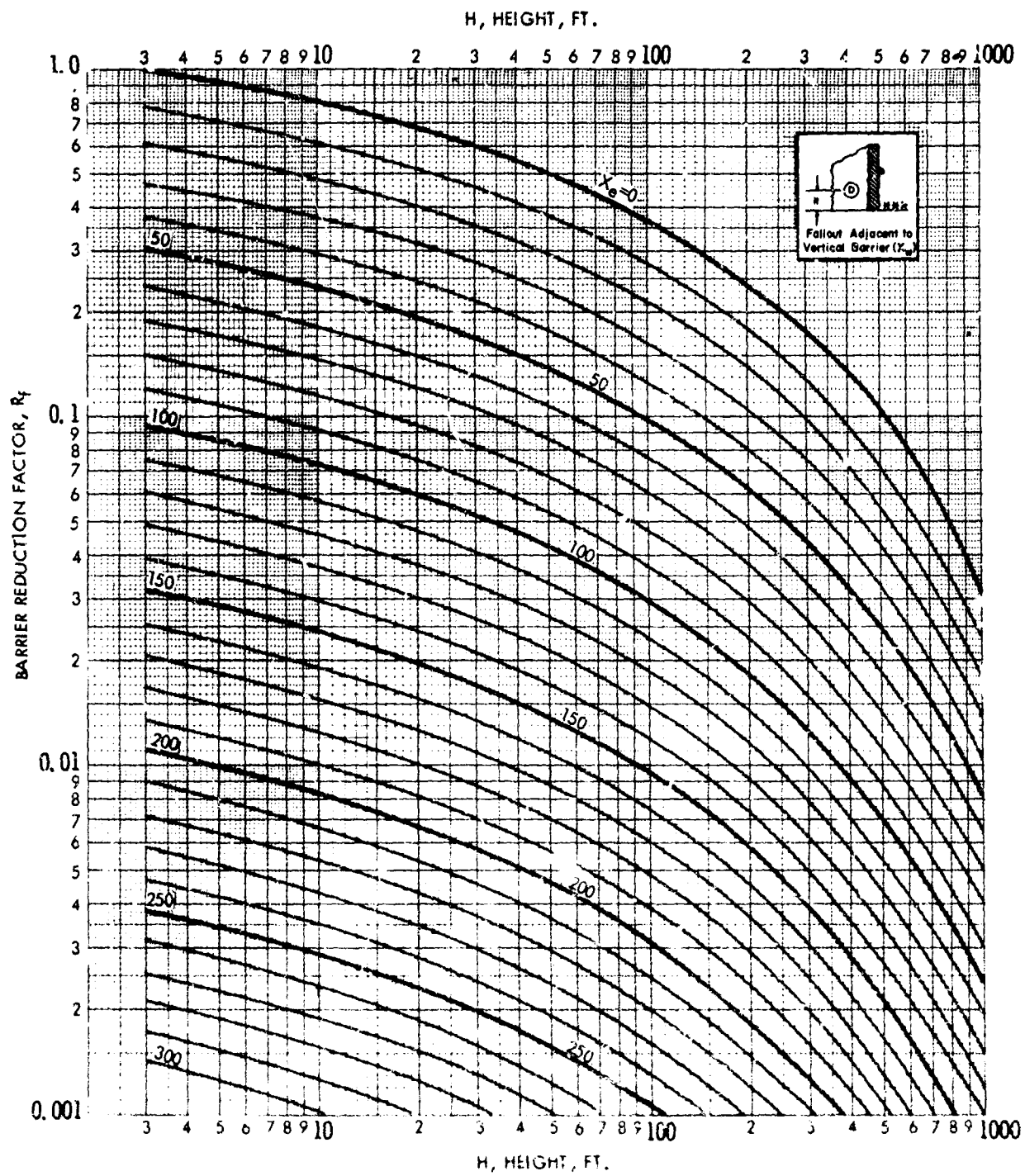
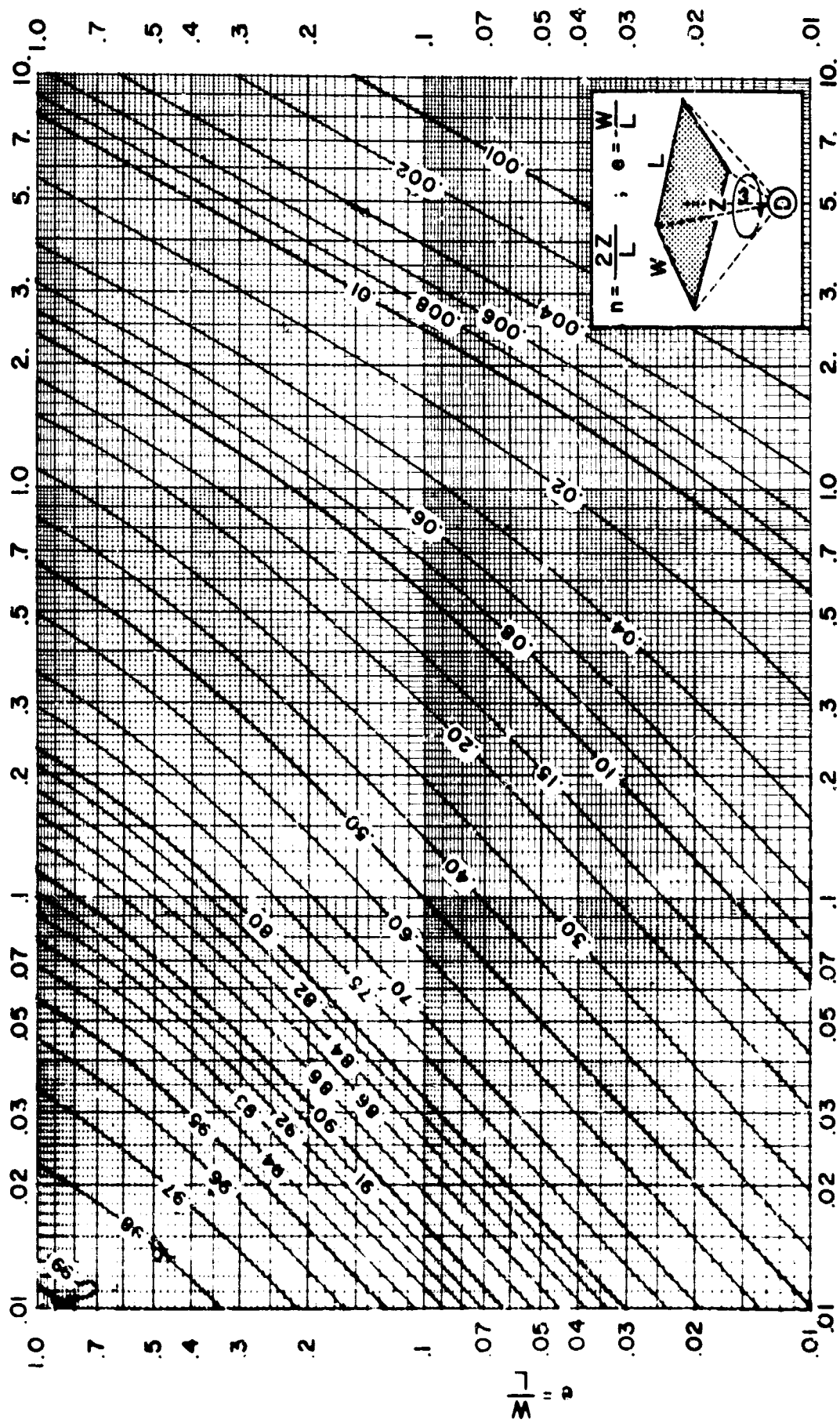


Chart 2. WALL BARRIER SHIELDING EFFECTS  $B_p(X_0)$  FOR VARIOUS HEIGHTS



$$n = \frac{2Z}{L}$$

Chart 3 Solid Angle Fraction Contours,  $\omega$ .

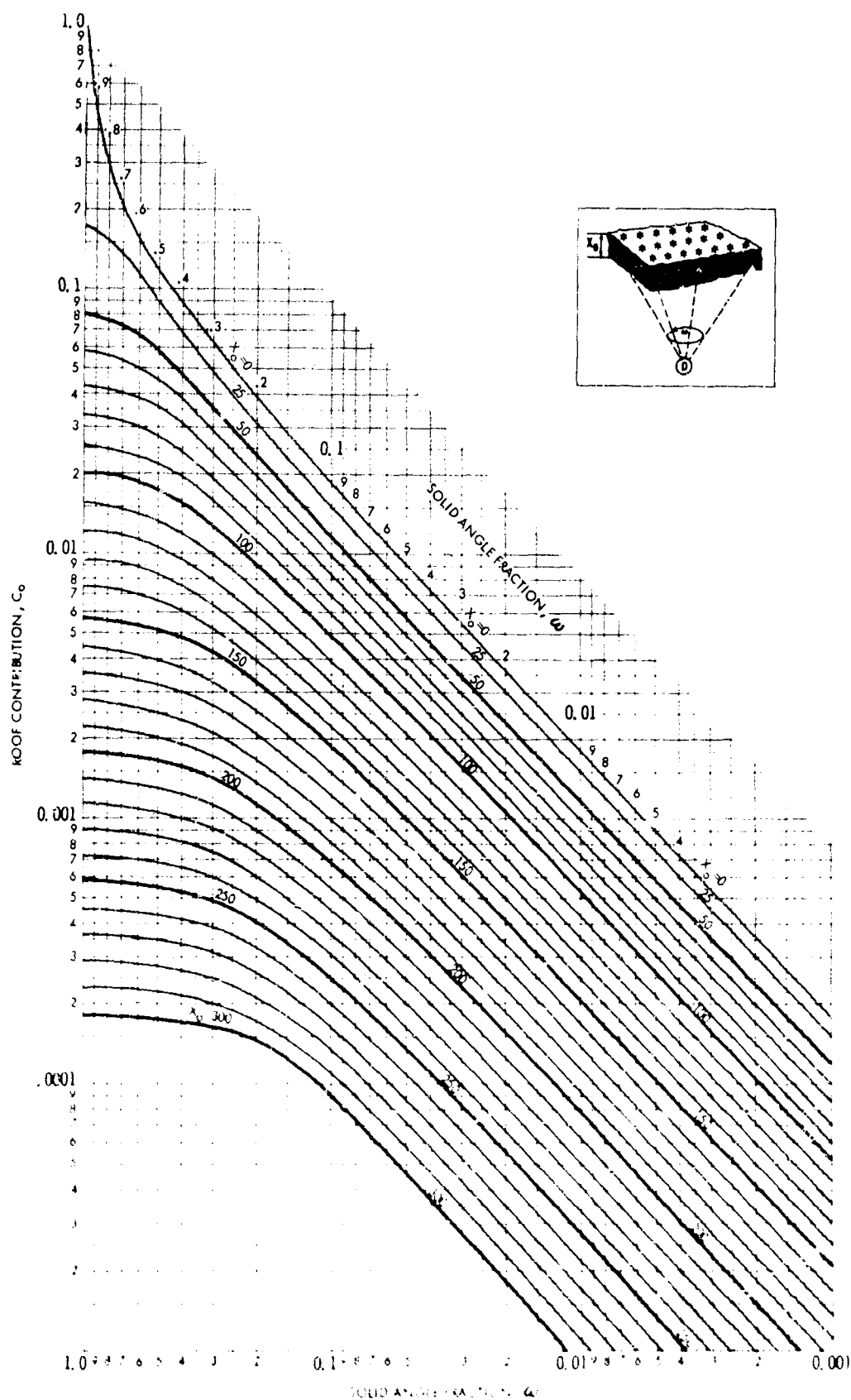


Chart 4. REDUCTION FACTOR FOR ROOF CONTRIBUTION  $C_0$

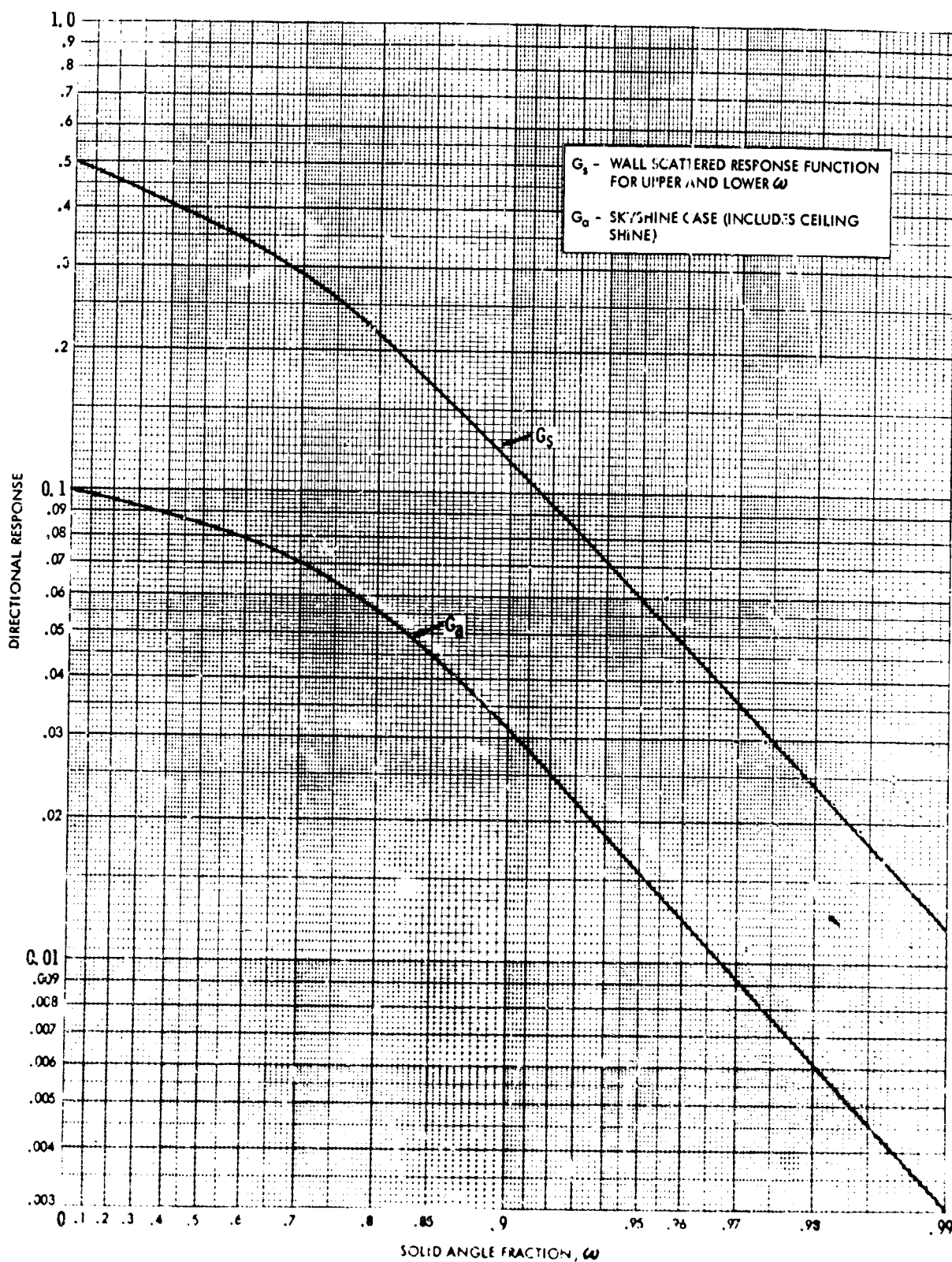


Chart 5. DIRECTIONAL RESPONSES, GROUND CONTRIBUTION,  $G_s$  &  $G_a$

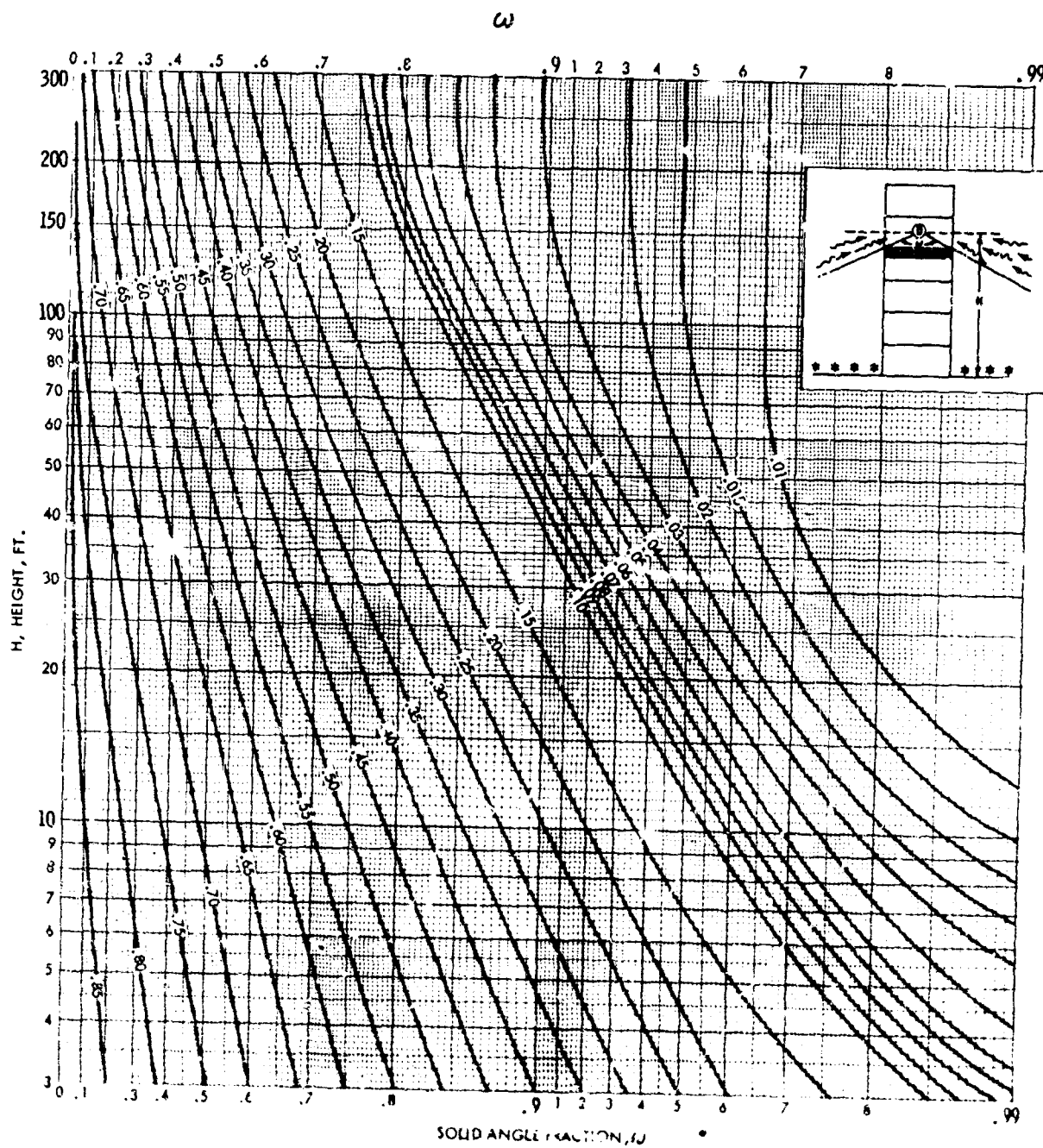


Chart 6. DIRECTIONAL RESPONSE FOR DIRECT RADIATION,  $G_d$ , FOR VARIOUS HEIGHTS

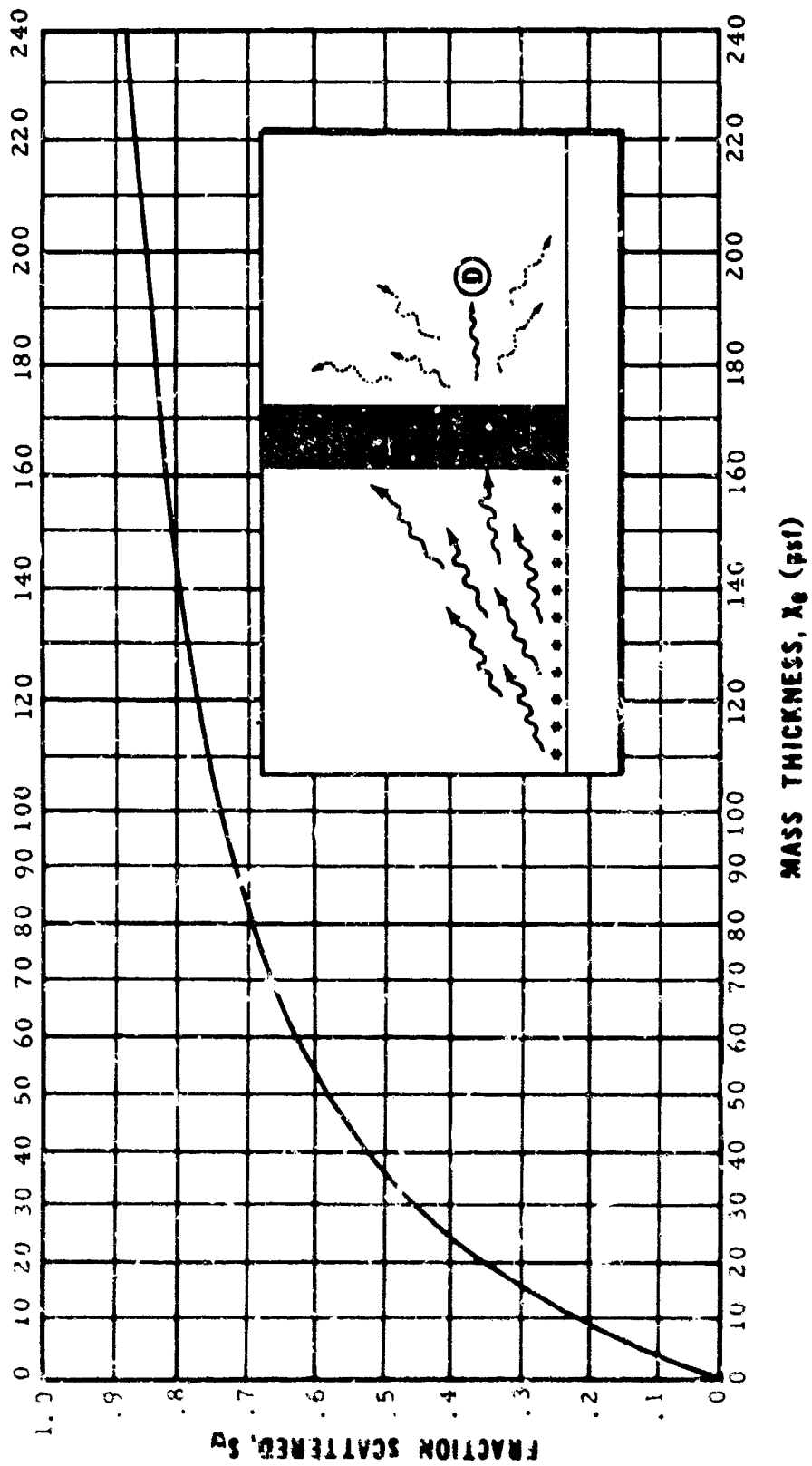


Chart 7. Fraction of Emergent Radiation Scattered in Wall Barrier,  $S_w$

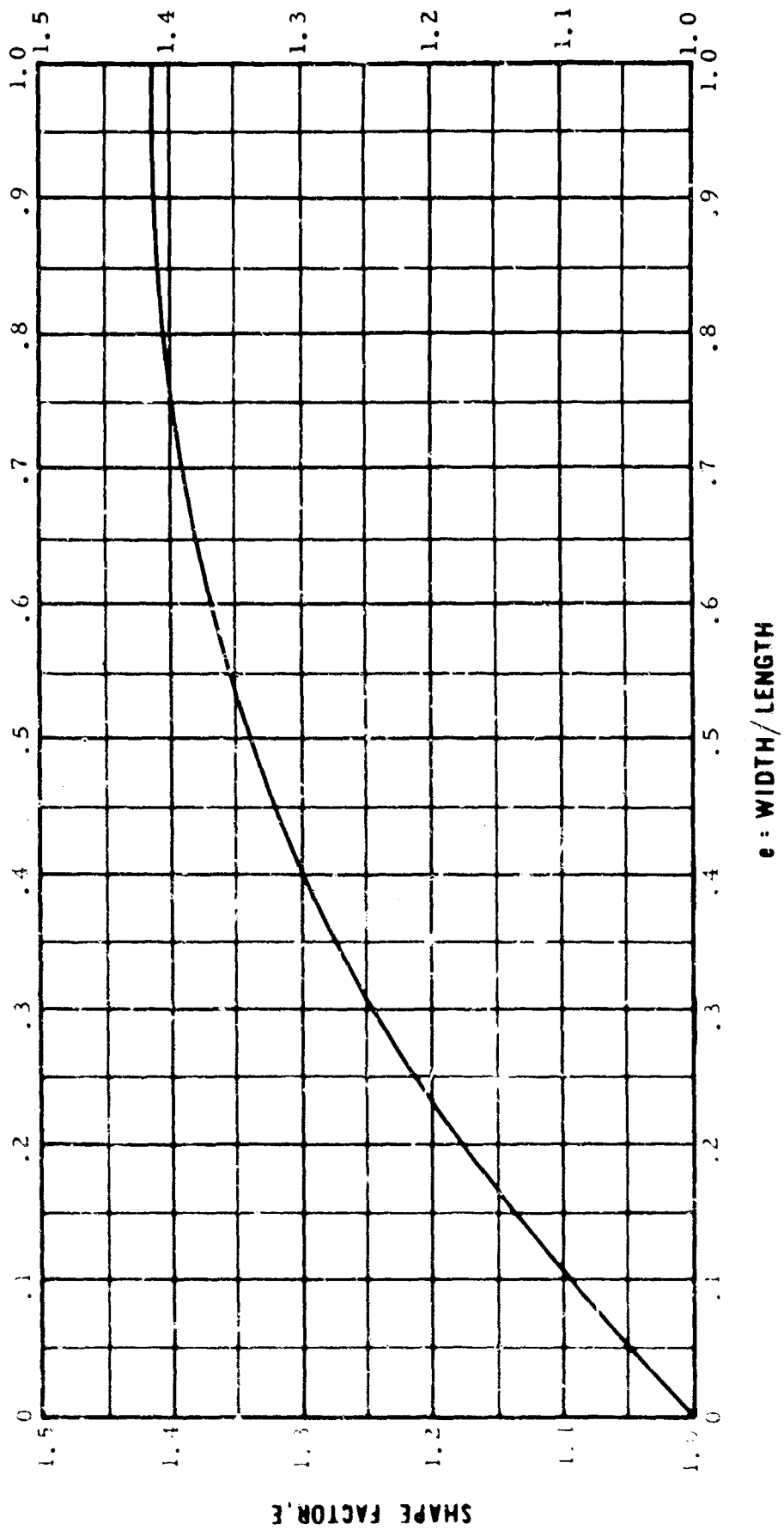


Chart 8. Shape Factor for Wall-scattered Radiation,  $E$



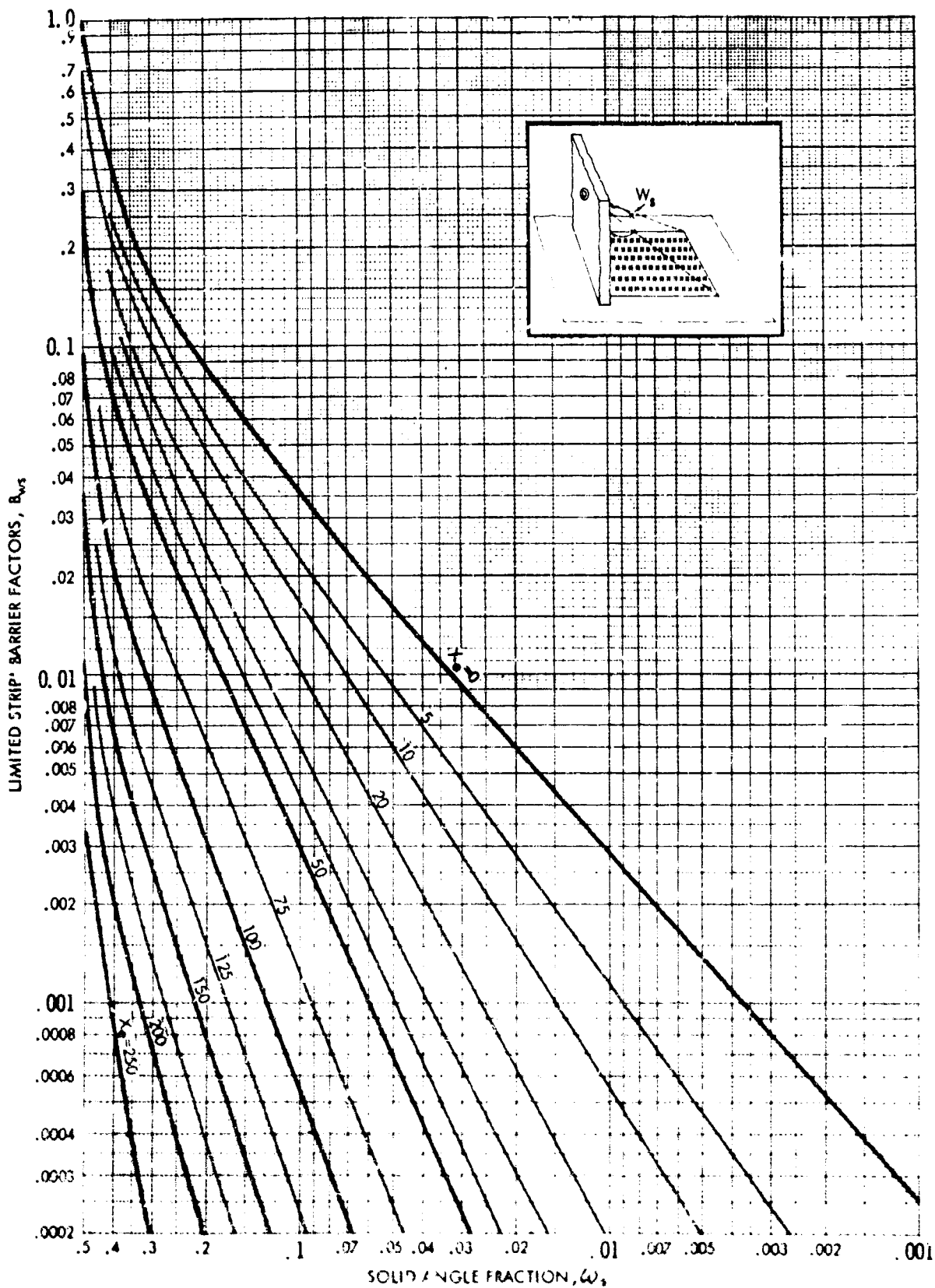


Chart 9. BARRIER REDUCTION FACTORS FOR WA 1-SCATTERED RADIATION  
FOR LIMITED STRIP OF CONTAMINATION

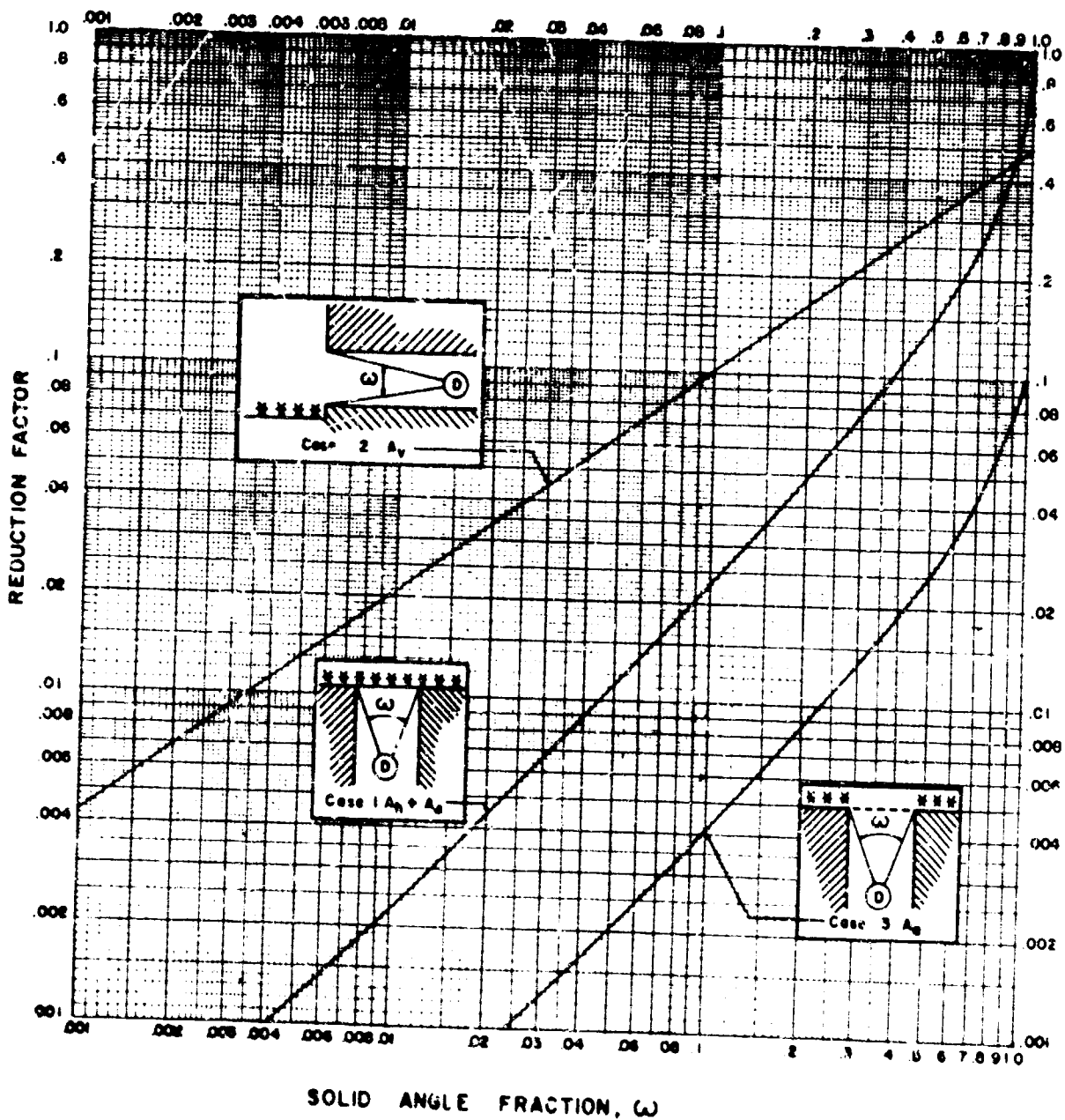


Chart 10. Reduction factors for passageways and shafts,  $A_v$ ,  $A_h + A_d$  &  $A_d$

## CHAPTER 5

### BASIC APPLICATION OF THE DETAILED PROCEDURE

#### 5.1 INTRODUCTION

The simplest cases to be analyzed by the detailed procedure consist of structures with rectangular floor plans, flat roofs, and with the detector located in the geometric center of the plan. Such structures are referred to as block houses. The analysis procedure is to determine the roof contribution,  $C_o$ , and the ground contribution,  $C_g$ , separately; then combine them to obtain the reduction factor. This chapter presents the analysis procedure for the determination of the reduction factor for these simple cases.

#### 5.2 COMBINING OR DIFFERENCING DIRECTIONAL RESPONSES

In determining the directional response for either wall-scattered or non-wall-scattered radiation from a given wall, it is usually necessary to combine, or difference, the directional responses of more than one solid angle fraction.

If, in Figure 5.1,  $G_s(\omega_u)$  and  $G_s(\omega_L)$  represent the directional responses for wall-scattered radiation reaching the detector from that portion of the wall respectively above and below the detector, then the total response for wall-scattered radiation from this wall is  $G_s(\omega_u) + G_s(\omega_L)$ . This is termed the combined response for wall-scattered radiation.

Similarly the combined response for non-wall-scattered radiation in this case would be  $G_d(\omega_L, H_d) + G_a(\omega_u)$ .

Figure 5.2 illustrates a two story structure having one story below grade with the detector located in the lower story. In this case the total response for wall-scattered radiation through the walls of the upper story is the differenced response for solid angle fractions  $\omega_u^1$  and  $\omega_u$ , i.e.  $G_s(\omega_u^1) - G_s(\omega_u)$ . The total response for non-wall-scattered radiation from this wall is the differenced response for skyshine only,  $G_a(\omega_u^1) - G_a(\omega_u)$ .

#### 5.3 PROCEDURE FOR EXAMPLE PROBLEMS

The example problems in this chapter use the same format. A similar procedure should be used by the analyst until he is thoroughly familiar with the systems of analysis. The procedure used here is:

1. Prepare a clear, single line sketch of the structure, preferably to scale.
2. Sketch in the applicable solid angle fractions.

3. Write the appropriate functional expressions.
4. Fill in the "score box". This is nothing more than a book-keeping aid.
5. Evaluate the functional expressions to obtain the roof and ground contributions.

With more complex structures it is necessary to include the use of fictitious buildings and sector analysis in this procedure (discussed: paragraph 5.7 and 5.10) but the basic technique remains the same.

#### 5.4 ROOF CONTRIBUTION, SIMPLE RECTANGULAR ROOFS

The roof contribution from a simple rectangular roof is a function of only two parameters: the solid angle fraction which measures the size of the roof, or contributing contaminated plane as seen by the detector, and the total overhead mass,  $X_0$ , which determines the barrier effect of the roof. If these two parameters are determined, the roof contribution can be read directly from chart 4. When more than one horizontal overhead barrier exists, the mass thickness,  $X_0$ , is the sum of these mass thicknesses. Thus in Example 5.2, Figure 5.2, the mass thickness,  $X_0$ , is 150 psf.

Example 5.1 illustrates this procedure for a simple roof. Note that chart 4 gives only the roof contribution from a circular or rectangular roof to a detector located beneath the geometric center of the roof. Thus all roof contributions must be found in terms of a circular or rectangular roof symmetrical about the detector.

#### 5.5 GROUND CONTRIBUTION, SIMPLE RECTANGULAR BUILDING

##### 5.5.1 ADJACENT WALL CASE

Figure 5.1 represents a simple rectangular building. The ground contribution is determined by writing the appropriate functional expression and then evaluating this expression using the charts in Chapter 4. To write the functional expression, it is first necessary to define the solid angle fractions which will determine the geometry terms, in this case  $\omega_U$  and  $\omega_L$ .

The wall scattered component is the combined response  $G_s(\omega_U) + G_s(\omega_L)$ . The non-wall-scattered component is  $G_d(\omega_L, H_d) + G_s(\omega_U)$ . The factors for the fractional portion of the emergent radiation which has been wall-scattered,  $S_w(X_e)$  and non-wall-scattered,  $(1 - S_w(X_e))$ , and the shape factor,  $E(e)$ , are then applied; the resulting geometry reduction factor for ground contribution is:

$$G_g = [G_d(\omega_L, H_d) + G_s(\omega_U)] [1 - S_w(X_e)] + [G_s(\omega_U) + G_s(\omega_L)] S_w(X_e) E(e)$$

When the barrier factor for the exterior wall is introduced, the functional expression becomes:  $C_g = G_g B_e(X_e, H)$

$$= \{ [G_d(\omega_L, H_d) + G_a(\omega_u)] [1 - S_w(X_e)] + [(G_s(\omega_u) + G_s(\omega_L)) S_w(X_e) E(e)] \} B_e(X_e, H)$$

This type of problem is illustrated in Example 5.1.

#### 5.5.2 STORY ABOVE THE DETECTOR

Figure 5.2 illustrates a basement detector location with the basement walls fully buried. In such cases, the only significant ground contribution is through the walls of the first story. It is possible for some radiation to reach the detector through the basement wall by first passing through the earth adjacent to this wall; however, this radiation is of importance only when the fall-out piles up against the wall. In most cases, radiation through basement walls need be considered only when that wall is partially exposed above grade (See paragraph 5.5.3).

The solid angle fractions needed to define the limits of the first story wall are shown in Figure 5.2. The functional expression is written with the net wall-scattered and non-wall-scattered components being the differenced, responses for  $\omega_u'$  and  $\omega_u$ .  $S_w(X_e)$  and  $E(e)$  are determined by the mass thickness and shape of the first story wall.

As all radiation coming through the first story wall must pass through both the wall and the floor slab there are two barrier factors:  $B_e(X_e, H)$ , which accounts for the barrier attenuation of the first story wall and is read from chart 2, and  $B_o'(X_o')$ , which corresponds to the floor slab and is read from  $B_o'(X_o')$  curve chart 1. Note that the barrier factor for the first floor slab,  $B_o'$ , is a function only of the single parameter of the mass thickness of that slab,  $X_o'$ .

The final functional expression is:

$$C_g = \underbrace{\{ [G_s(\omega_u') - G_s(\omega_u)] S_w(X_e) E(e) + [G_a(\omega_u') - G_a(\omega_u)] [1 - S_w(X_e)] \}}_{\text{Geometry Factor}} \underbrace{B_e(X_e, H) B_o'(X_o')}_{\text{Barrier Factors}}$$

The non-wall-scatter radiation in this case consists entirely of skyshine as it originates above the plane of the detector.

Example 5.2 illustrates this procedure.

### EXAMPLE 5.1

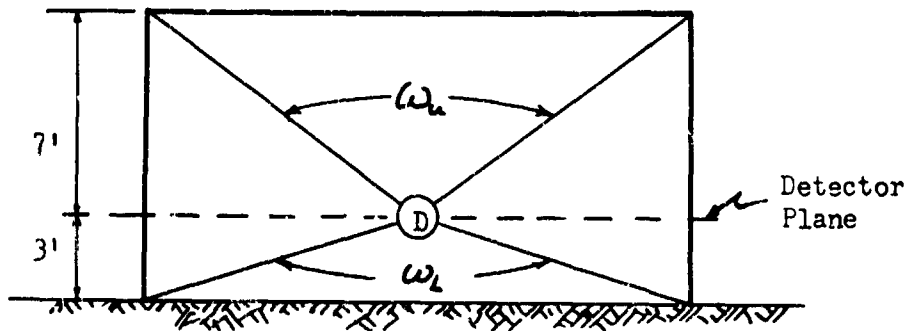


Figure 5.1

Given: Structure shown in Figure 5.1 with centrally located detector.

Length = 80'

Width = 60'

Mass Thickness:  $X_e = 100$  psf

$X_o = 80$  psf

	W	L	Z	$e=W/L$	$n=2Z/L$	Chart <sup>G</sup> 3	Chart <sup>G</sup> 5	Chart <sup>G</sup> 5	Chart <sup>G</sup> 6
$\omega_u$	60	80	7'	.75	.175	.81	.20	.052	---
$\omega_L$	60	80	3'	.75	.075	.92	.092	---	.36

$$S_w(X_e) = S_w(100\text{psf}) = .73 \text{ (chart 7 )} \quad E(e) = E(.75) = 1.4 \text{ (Chart 8 )}$$

$$B_e(X_e, H) = E_e(100\text{psf}, 3') = .095 \text{ (Chart 2 )}$$

Ground Contribution:

$$C_g = \{ [G_d(\omega_L, H_d) + G_a(\omega_u)] [1 - S_w(X_e)] + [G_s(\omega_L) + G_s(\omega_u)] S_w(X_e) E(e) \} B_e(X_e, H)$$

$$= [ (.36 + .052)(1 - .73) + (.092 + .20)(.73)(1.4) ] (.095) = 0.038$$

Roof Contribution :

$$C_o = C_o(\omega_u, X_o) = C_o(.81, 80\text{psf}) = .036 \text{ (Chart 4)}$$

$$R_f = C_o + C_g = .035 + .038 = .073$$

$$P_f = \frac{1}{R_f} = \frac{1}{.073} = \underline{\underline{14}}$$

Diagram illustrating the geometry of a rectangular detector plane. The plane is divided into two regions by a horizontal line. The upper region has a height of 14' and a width of  $X_{RDPF}$ . The lower region has a height of 10' and a width of  $X_C$ . The detector is located at the bottom center, labeled  $D$ . The angle between the vertical axis and the line connecting  $D$  to the top edge is labeled  $\omega_u'$ . The angle between the vertical axis and the line connecting  $D$  to the bottom edge is labeled  $\omega_u$ . The angle between the vertical axis and the line connecting  $D$  to the right edge is labeled  $X_O'$ . The horizontal line is labeled "Detector Plane".

**Given:** Structure shown in Figure 5.2

Length = 110 feet

Mass Thickness:  $X_e = 70 \text{ psf}$

$$X_0 = 50 \text{ psf}$$
$$Y_{\text{roof}} = 100 \text{ psf}$$

	W	L	Z	$\sigma=W/L$	$n=2Z/L$	$\omega$ Chart 3	$G_s$ Chart 5	$G_a$ Chart 5
$\omega_1^*$	90	110	24	.82	.44	.60	.33	.079
$\omega_1$	90	110	10	.82	.16	.82	.19	.05

$$S_w(x_o) = S_w(70\text{psf}) = .66 \text{ (Chart 7)} \quad E(e) = E(.82) = 1.41 \text{ (Chart 8)}$$

$$B_o(X_o, H) = B_o(70\text{psf}, 3') = .18(\text{Char. } 2) \text{ H. taken as } 3' \text{ for basement cases.}$$

$$B'_0(X'_0) = B'_0(50\text{psf}) = .002 \left( B'_0(X'_0) \text{ Curve. Chart 1} \right) \text{ cases.}$$

### Example 5.2 (Continued)

Ground Contribution: In this case the non-wall-scattered radiation consists entirely of skyshine radiation as it all originates above the detector plane. Any radiation which might come through the earth adjacent to the basement wall is ignored.

$$C_g = \{ [G_a(\omega_u^i) - G_a(\omega_u)] [1 - S_w(X_e)] + [G_s(\omega_u^i) - G_s(\omega_u)] S_w(X_e) E(e) \} B_e(X_e, H) B_g^i(X_0^i) \\ = [(.079 - .05)(1 - .66) + (.33 - .19)(.66)(1.41)] (.18)(.062) = \underline{.0016}$$

Roof Contribution: The total overhead mass thickness,  $X_0$ , is the sum of the mass thicknesses of the roof and ground floor slab or 150 psf. The solid angle fraction subtended by the contaminated roof is  $\omega_u^i$ .

$$C_o = C_o(\omega_u^i, X_0) = C_o(.60, 150\text{psf}) = .0056 \quad (\text{Chart 4})$$

$$R_f = C_o + C_g = .0056 + .0016 = \underline{.0072}$$

$$P_f = \frac{1}{R_f} = \frac{1}{.0072} = \underline{139}$$

### 5.5.3 PARTIALLY EXPOSED BASEMENTS

As the exposure of a basement wall increases, the magnitude of the ground contribution through that wall increases rapidly in comparison to that through the first story wall. This is primarily due to attenuation of the first story contribution by the floor slab. The functional expression for ground contribution through basement walls is similar to that for the contribution of first story walls to a basement detector, except that no barrier factor appears for the floor slab. The total ground contribution is the sum of that the contributions through the first story walls and the basement walls. Example 5.3 illustrates the case of the partially exposed basement wall.

### 5.5.4 STORY BELOW THE DETECTOR

When a detector is located on an upper floor of a multi-storied building, the ground contribution through the walls of the story below the detector must be considered. This is especially true if the floors are thin or if the walls of that story contain a high percentage of apertures.

The functional expression for this case is illustrated in Example 5.4. Note that all non-wall-scattered radiation is ground direct radiation as it originates below the detector plane. Again there



are two separate barrier factors; one for the exterior wall,  $B_e(X_e, H)$  and a second for the floor beneath the detector,  $B_f(X_f)$ . The floor barrier factor is obtained from  $B_f(X_f)$ , Chart 1, with  $X_f$  as the only parameter.

### EXAMPLE 5.3

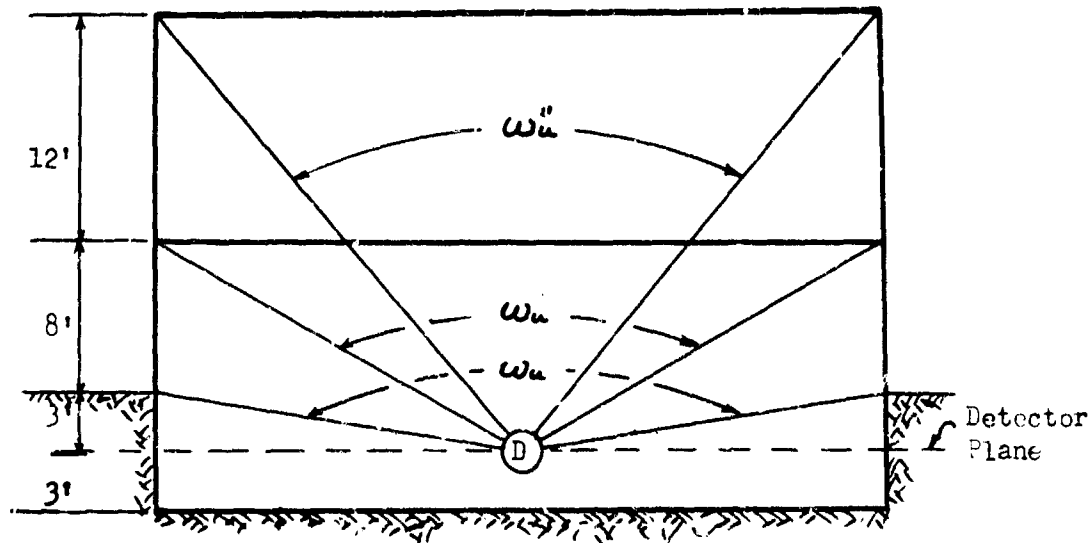


Figure 5.3

Given: Structure shown in Figure 5.3

Detector is centrally located in the basement

Length = 100 feet

Width = 50 feet

Mass Thicknesses:  $X_g = 80$  psf (first story)

$X_e = 100$  psf (basement)

$X_o = 60$  psf

$X_{\text{roof}} = 100$  psf

	W	L	H	$\sigma = W/L$	$\sigma = H/L$	$G$	$G_g$	$G_e$
						Chart 3	Chart 5	Chart 5
$\omega_u''$	50	100	23	.50	.4	.47	.39	.086
$\omega_u'$	50	100	11	.50	.27	.70	.30	.069
$\omega_u$	50	100	3	.50	.03	.91	.10	.029

### Example 5.3 (Continued)

Ground Contribution: The contribution through the basement walls and the first story walls must be determined separately, then combined for the total ground contribution.

Basement walls:

$$C_g = \{ [G_a(\omega_u^I) - G_s(\omega_u^I)] [1 - S_w(X_e)] + [G_s(\omega_u^I) - G_s(\omega_u^I)] S_w(X_e) E(e) \} B_e(X_e, H)$$

$$S_w(X_e) = S_w(100 \text{ psf}) = 0.73 \text{ (Chart 7)}$$

$$E(e) = E(.5) = 1.34 \text{ (Chart 8)}$$

$$B_e(X_e, H) = B_e(100 \text{ psf}, 3') = .095$$

$$C_g = [ (.069 - .029)(1 - .73) + (.28 - .10)(.73)(1.34) ] (.095) = .0177$$

First Story Walls:

$$C_g = \{ [G_a(\omega_u^{II}) - G_s(\omega_u^I)] [1 - S_w(X_e)] + [G_s(\omega_u^{II}) - G_s(\omega_u^I)] S_w(X_e) E(e) \} B_e(X_e, H) B'_0(X'_0)$$

$$S_w(X_e) = S_w(80 \text{ psf}) = .69 \text{ (Chart 7)}$$

$$B_e(X_e, H) = B_e(80 \text{ psf}, 3') = .15 \text{ (Chart 2)}$$

$$B'_0(X'_0) = B'_0(60 \text{ psf}) = .04 \text{ (} B'_0(X'_0) \text{ Curve, Chart 1)}$$

$$C_g = [ (.086 - .069)(1 - .69) + (.39 - .28)(.69)(1.34) ] (.15)(.04) = .00064$$

$$\text{Total ground contribution} = .00064 + .0177 = .0183$$

Roof Contribution:

$$X_0 = X_{\text{roof}} + X'_0 = 100 + 60 = 160 \text{ psf } \omega_u^{II} = .47$$

$$C_0(\omega_u^{II}, X_0) = C_0(.47, 160 \text{ psf}) = .0041$$

$$R_f = C_0 + C_g = .0183 + .0041 = .0224$$

$$P_f = \frac{1}{R_f} = \frac{1}{.0224} = 45$$

# EXAMPLE 5.4

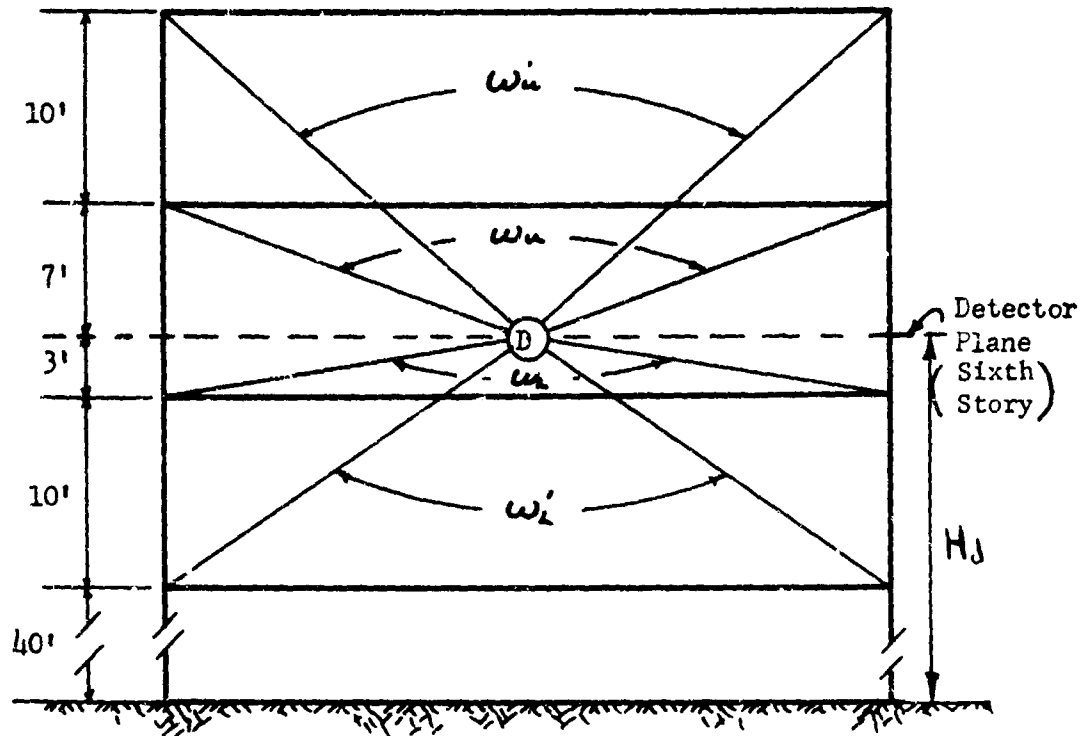


Figure 5.4

Given: Structure shown in Figure 5.4

Detector is centrally located on the sixth story

Length = 100'

Width = 75'

Mass thickness:  $X_o = 80$  psf all stories

$X_o^s = 60$  psf

$X_r = 60$  psf

$X_r = 90$  psf

$X_o = X_r + X_o^s = 150$  psf

	$W$	$L$	$Z$	$\alpha = W/L$	$n = 2Z/L$	$\omega$	$G_a$	$G_a$	$G_d$
						Chart 3	Chart 5	Chart 5	Chart 4
$\omega_u^s$	75'	100'	17'	.75	.34	.66	.29	.072	---
$\omega_u$	75'	100'	7'	.75	.14	.85	.105	.045	---
$\omega_L$	75'	100'	3'	.75	.06	.93	.08	---	.04
$\omega_L'$	75'	100'	13'	.75	.26	.73	.26	---	.32

$$S_w(X_e) = S_w(80\text{psf}) = .69 \quad (\text{Chart } 7)$$

$$E(e) = E(.75) = 1.40 \quad (\text{Chart } 8)$$

Ground Contribution:

a. Sixth story

$$C_g = \{ [G_d(\omega_L, H_d) + G_a(\omega_u)] [1 - S_w(X_e)] + [G_s(\omega_u) + G_s(\omega_L)] S_w(X_e) E(e) \} B_e(X_e, H)$$

$$B_e(X_e, H) = B_e(80\text{psf}, 53') = .065 \quad (\text{Chart } 2)$$

$$C_g = [(.04 + .045)(1 - .69) + (.165 + .08)(.69)(1.4)] (.065) = .0170$$

b. Fifth story. Note that all non-wall-scattered radiation is ground direct radiation.

$$C_g = \{ [G_d(\omega_L', H_d) - G_d(\omega_L, H_d)] [1 - S_w(X_e)] + [G_s(\omega_L') - G_s(\omega_L)] S_w(X_e) E(e) \} \{ B_e(X_e, H) B_f(X_f) \}$$

$$B_e(X_e, H) = B_e(30\text{psf}, 53') = .065 \quad (\text{Chart } 2)$$

$$B_f(X_f) = B_f(60\text{psf}) = .062 \quad (\text{Case 1, Chart } 1)$$

$$C_g = [(.32 - .04)(1 - .69) + (.26 - .08)(.69)(1.4)] (.065)(.062) = .00105$$

c. Seventh story. All non-wall-scattered radiation in sky-shine radiation.

$$C_g = \{ [G_a(\omega_u') - G_a(\omega_u)] [1 - S_w(X_e)] + [G_s(\omega_u') - G_s(\omega_u)] S_w(X_e) E(e) \} B_e(X_e, H) B_o'(X_o')$$

$$B_e(X_e, H) = B_e(80\text{psf}, 53') = .065 \quad (\text{Chart } 2)$$

$$B_o'(X_o') = B_o'(60\text{psf}) = .045 \quad (B_o'(X_o') \text{ Curve, Chart 1})$$

$$C_g = [(.072 - .045)(1 - .69) + (.29 - .165)(.69)(1.4)] (.065)(.045) = .00038$$

Total Ground Contribution:

$$C_g = .0170 + .00105 + .00038 = .0184$$

Roof Contribution:

$$X_o = 150\text{psf } \omega_u' = .68$$

$$C_o = C_o(\omega_u', X_o) = C_o(.68, 150\text{psf}) = .0056$$

$$R_f = C_o + C_g = .0056 + .0184 = .024$$

$$P_f = \frac{1}{R_f} = \frac{1}{.024} = .42$$

## 5.6 INTERIOR PARTITIONS

### 5.6.1 EFFECT ON GROUND CONTRIBUTIONS

The presence of an interior partition may have considerable influence on the reduction factor, depending on its mass thickness and extent. While the presence of such a partition will affect both the geometry and the barrier reduction factors, only the barrier effects are considered. The difference in geometry effects between parallel (to the exterior wall) and perpendicular partitions is ignored partly due to the uncertainty of these effects and partly because of the complications they would introduce into the calculations. An interior partition barrier reduction factor,  $B_1(X_1, 3')$  is applied to radiation which passes through the interior partition. The path of radiation within a structure is represented by straight lines drawn from the exterior walls to the detector. The procedure is to work the problem as if the interior partition did not exist, then apply the barrier reduction factor obtained from chart 2 for a height of three feet. Three foot height is always used because the height above the contaminated plane was considered in determining the basic exterior wall barrier factor.

When more than one partition exists between the detector and the source, the mass thicknesses are added and a single interior partition barrier factor is determined. Thus the barrier reduction factor for three successive 25 psf partitions would be  $B_1(75\text{psf}, 3')$ .

### 5.6.2 EFFECT ON ROOF CONTRIBUTION

As stated in the paragraph 5.6.1, radiation which passes through an interior partition will be attenuated by that partition. The principle problem with roof contribution is not in finding the barrier reduction factor but in determining what portion of the roof contribution is affected by this partition. Figure 5.5 illustrates the ideal case of a core shelter, or a box within a box. The only radiation from the roof affected by the partition is that which originates outside the core, on the peripheral roof area. The core roof contribution and the peripheral roof contribution must be determined separately and the interior partition barrier reduction factor applied only to the peripheral contribution. If  $C_o(\omega_u, X_o)$  is the roof contribution from the total roof area, ignoring the interior partition, and  $C_c(\omega_u^*, X_o)$  is the roof contribution from the core roof only; then the difference,  $C_o(\omega_u, X_o) - C_c(\omega_u^*, X_o)$ , is the peripheral roof contribution before application of the partition barrier reduction factor. The total roof contribution is:

$$C_o = \underbrace{C_c(\omega_u^*, X_o)}_{\text{Core Contribution}} + \underbrace{[C_o(\omega_u, X_o) - C_c(\omega_u^*, X_o)]}_{\text{Peripheral Contribution}} B_1(X_1)$$

The interior partition barrier reduction factor for roof contribution,  $B_1'(X_1)$  is obtained from a separate curve, Chart 1.  $B_1'(X_1)$

(refer to paragraph 4.2.7). This factor is different from the one used for interior partitions for ground contribution,  $B_1(X_1, 3')$ , and the two must not be interchanged. There are three important considerations in differencing roof contributions:

1. The terms being differenced must be functions of the same value of  $X_0$ .
2. The solid angle fractions must be functions of the same distance.
3. Each value selected from chart 4 is representative of the roof contribution from a circular or rectangular area SYMMETPICAL about the detector.

These three conditions must always be satisfied when differencing roof contributions.

Example 5.6 illustrates another use of the differencing technique for roof contribution.

#### EXAMPLE 5.5

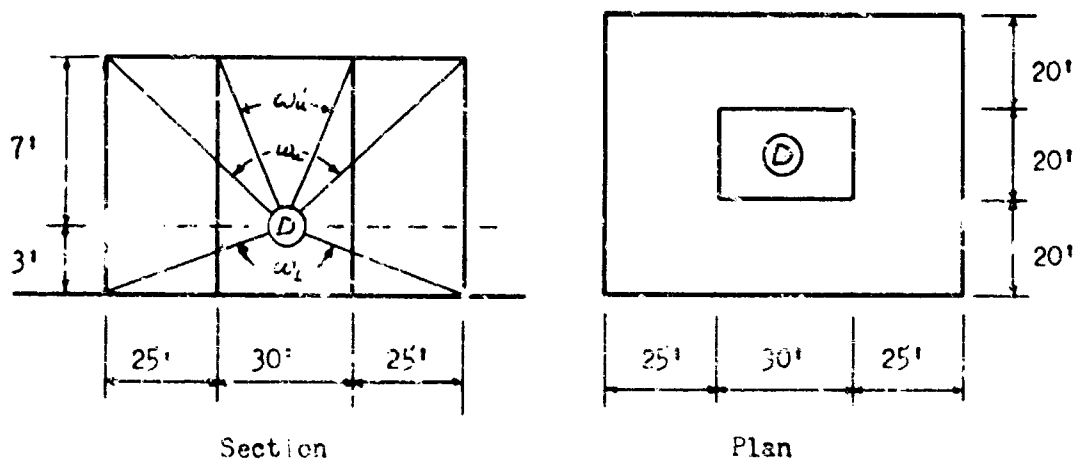


Figure 5.5

Given: Structure shown in Figure 5.5

Mass Thicknesses:  $X_1 = 100 \text{ psf}$      $X_2 = 40 \text{ psf}$      $X_0 = 80 \text{ psf}$

Ground Contribution: This is the same structure used in Example 5.1 with the addition of a 40 psf interior partition. The only change in the ground contribution is the inclusion of a barrier reduction factor  $B_i(X_i, 3')$  for the interior partition.

$$C_g = G_g B_e \cdot B_i(X_i, 3')$$

$$G_g B_e = .038 \text{ (Example 5.1)}$$

$$B_i(X_i, 3') = B_i(40\text{psf}, 3') = .38 \quad (\text{Chart } 2)$$

$$C_g = .038 \times .38 = \underline{.0145}$$

Roof Contribution: It is necessary to distinguish between the core roof contribution and the peripheral roof contribution, as only the latter is influenced by the interior partition. This is done by differencing the roof contribution as discussed in paragraph 5.6.2.

$$C_o = C_o(\omega_u', X_o) + [C_o(\omega_u, X_o) - C_o(\omega_u', X_o)] B_i'(X_i)$$

	W	L	Z	e=W/L	m=2Z/L	$\omega$ Chart 3	$X_o$	$C_o$ Chart 4
$\omega_u$	60	80	7'	.75	.18	.81	80	.035
$\omega_u'$	20	30	7'	.67	.47	.54	80	.030

$$B_i'(X_i) = B_i'(40\text{psf}) = .26 \text{ Chart 1, } B_i'(X_i) \text{ Curve}$$

$$C_o = .030 + [.035 - .030] .26 = .031$$

$$R_f = C_o + C_g = .031 + .0145 = .0455$$

$$P_f = \frac{1}{R_f} = \frac{1}{.0455} = 22$$

## 5.7 AZIMUTHAL SECTORS

The buildings discussed in the preceeding paragraphs have been block houses with only one type of wall construction. As few real buildings fall into this category, the radiation arriving at a detector from two different directions may have passed through barriers of quite a different nature. Further, all detector positions will not be the center of a rectangular area and thus geometry factors may vary from wall to wall within a building. It, therefore, is usually necessary to separately analyze the different sectors of an actual building. This is done by using azimuthal sectors.

Consider a detector location in the middle of a block house. If it is assumed the ground contribution through each degree of azimuth about the detector is equal, then the ground contribution through any given wall will be directly proportional to the plane angle subtended by that wall at the detector. The portion of a circle represented by that angle is the azimuthal sector of that wall. Expressed as an equation:

$$A_z = \frac{\text{The plane angle subtended}}{360^\circ}$$

The use of azimuthal sectors is discussed in paragraphs 5.8 and 5.10, and is illustrated in Examples 5.9 through 5.11.

## 5.8 WINDOWS AND DOORWAYS

### 5.8.1 GENERAL

The contribution through windows and doorways may be a large fraction of the total ground contribution. The contributions through these apertures must be determined, and the contribution through the adjacent solid walls must be adjusted to reflect the presence of the apertures. This is done by considering two separate buildings, each with the same size and shape as the actual building, but one with solid wall construction throughout and the other composed entirely of glass. The ground contribution from the analysis of these two buildings is weighted by the actual amount of aperture and solid wall present. The location of the aperture is also considered, as this determines the nature and magnitude of the radiation which reaches the detector. A detector located above the sill of an aperture will receive both ground direct and skyshine radiation through that aperture while a detector at or below sill level will receive only skyshine radiation through the aperture. For convenience, apertures are normally considered to have a mass thickness of zero.



# EXAMPLE 5.6

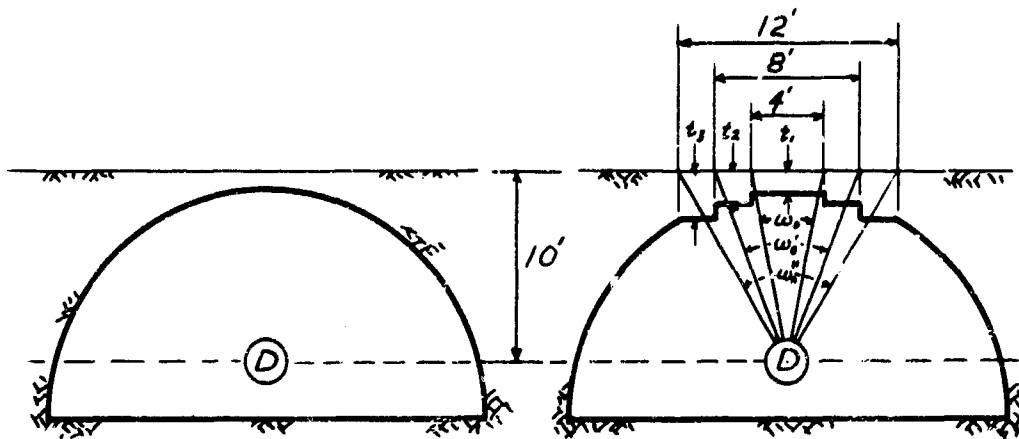


Figure 5.6a

Figure 5.6b

Given: Underground Arch shown in Figure 5.6a

Length = 40 ft

Mass Thickness:  $U = 120\text{psf}$

$$X_0 = t_1 U = 1.0 \times 120 = 120\text{psf}$$

$$X'_0 = t_2 U = 1.5 \times 120 = 180\text{psf}$$

$$X''_0 = t_3 U = 2.5 \times 120 = 300\text{psf}$$

Using these values of mass thickness, the arch is equated to an idealized flat roofed structure as shown in Figure 5.6b.

Roof Contribution: For clarity, the roof contribution is determined in three steps.  $C_0$  corresponds to the roof contribution through mass thickness  $X_0$ ,  $C'_0$  to that through  $X'_0$  and  $C''_0$  through  $X''_0$ .

		L	l	$\phi = W/L$	$n = 2l/L$	$\omega$
$\omega_0$	4	40	10	.10	.50	.11
$\omega'_0$	8	40	10	.20	.50	.20
$\omega''_0$	12	40	10	.30	.50	.30

$$C_0 = C_0(\omega_0, X_0) = C_0(.11, 120\text{psf}) = .0035$$

$$C'_0 = C_0(\omega'_0, X'_0) - C_0(\omega_0, X'_0) = C_0(.20, 180\text{psf}) - C_0(.11, 180\text{psf}) = .0017 - .0011$$

$$C''_0 = C_0(\omega''_0, X''_0) - C_0(\omega'_0, X''_0) = C_0(.30, 250\text{psf}) - C_0(.20, 250\text{psf}) = .0006 - .0004 = .0002$$

### Example 5.6 (Continued)

Total Roof Contribution: = .0035 + .0006 + .00009 = .0042

As there is no ground contribution  $R_f = .0042$

$$P_f = \frac{1}{R_f} = \frac{1}{.0042} = 238$$

In this solution it is assumed no significant radiation enters the structure from beyond  $\omega_0''$ . Examination of the magnitude of  $C_0''$  indicates this is a reasonable assumption. Notice in each case of differencing roof contributions, the mass thicknesses were the same for each term and the Z distances the same for both solid angle fractions.

-----

### 5.8.2 STORY OF THE DETECTOR

In Figure 5.7, the detector is on an upper floor of a multi-storied building with apertures. It is convenient to analyze a wall of this type in successive horizontal strips. In this way, the ground contribution through the solid strips below and above the windows can be determined as previously discussed. The strip containing the windows is analyzed first as a solid strip, then as a continuous window. The former is weighted by the decimal fraction of solid wall within that strip,  $(1-P_a)$ , and the latter by the fraction of apertures,  $P_a$  (when  $P_a$  is the perimeter ratio of apertures). The functional equations for ground contribution through this wall are:

#### 5.8.2.1 Solid Wall Below Windows

$$C_g = \{ G_s(\omega_L) S_w(X_e) E(e) + [G_d(\omega_L, H_d)] [1 - S_w(X_e)] \} B_e(X_e, H)$$

#### 5.8.2.2 Solid Wall Above Windows

$$C_g = \{ [G_s(\omega_u) - G_s(\omega_a)] S_w(X_e) E(e) + [G_a(\omega_u) - G_a(\omega_a)] [1 - S_w(X_e)] \} B_e(X_e, H)$$

#### 5.8.2.3 Solid Wall Between Windows

$$C_g = \{ [G_s(\omega_a) S_w(X_e)] + [G_a(\omega_a)] [1 - S_w(X_e)] \} B_e(X_e, H) (1 - P_a)$$

#### 5.8.2.4 Total Solid Wall - By collecting all terms for solid wall contributions, one functional expression can be written:

$$C_g = \{ [G_d(\omega_L, H_d) + G_a(\omega_u) - P_a G_a(\omega_a)] [1 - S_w(X_e)] + [G_s(\omega_L) + G_s(\omega_u) - P_a G_s(\omega_a)] S_w(X_e) E(e) \} B_e(X_e, H)$$

#### 5.8.2.5 Windows

$$C_g = \left\{ \cancel{G_a(\omega_a) S_w(x_e) E(e)} + G_a(\omega_a) \overset{1.0}{[1 - \cancel{S_w(x_e)}]} \right\} B_e(0, H) P_a$$

$$C_g = [G_a(\omega_a)] B_e(0, H) P_a$$

In paragraph 5.8.2.5, note that the value of  $S_w = 0$  (for zero mass thickness) causes the equation to reduce to the final form wherein only skyshine is considered. The barrier reduction factor,  $B_e(0, H)$ , is not 1.0 except in the special case of  $H = 3$  feet.

This procedure is applicable for windows with sills and tops at the same height spaced more or less evenly about the perimeter of the building. For isolated windows or for windows with uneven spacing, the azimuthal sector of apertures,  $Az_a$ , should be substituted for  $P_a$ .

#### 5.8.3 ADJACENT STORIES

When considering adjacent stories, the actual location of the apertures is of less importance, and only the extent or percentage of apertures is considered. This percentage, expressed as a decimal fraction is defined as:

$$Ap = \frac{\text{Area of Apertures}}{\text{Area of Wall}}$$

In Figure 5.7, it is required to find the ground contribution through the wall of the story below the detector. The analysis is performed first for a solid wall, then for a wall composed completely of apertures, the results being weighted by the appropriate value of  $(1 - Ap)$  and  $Ap$ . The functional expressions are:

##### 5.8.3.1 Solid Wall

$$C_g = \left\{ [G_a(\omega_L') - G_a(\omega_L)] S_w(x_e) E(e) + [G_d(\omega_L', H_d) - G_d(\omega_L, H_d)] [1 - S_w(x_e)] \right\} \{ B_e(x_e, H) B_f(x_f) (1 - Ap) \}$$

##### 5.8.3.2 Windows

$$C_g = [G_d(\omega_L', H) - G_d(\omega_L, H_d)] B_e(0, H) B_f(x_f) Ap$$

Again the aperture term contains only non-wall-scattered radiation. The analysis of a structure with apertures is illustrated in Example 5.7.

EXAMPLE 5.7

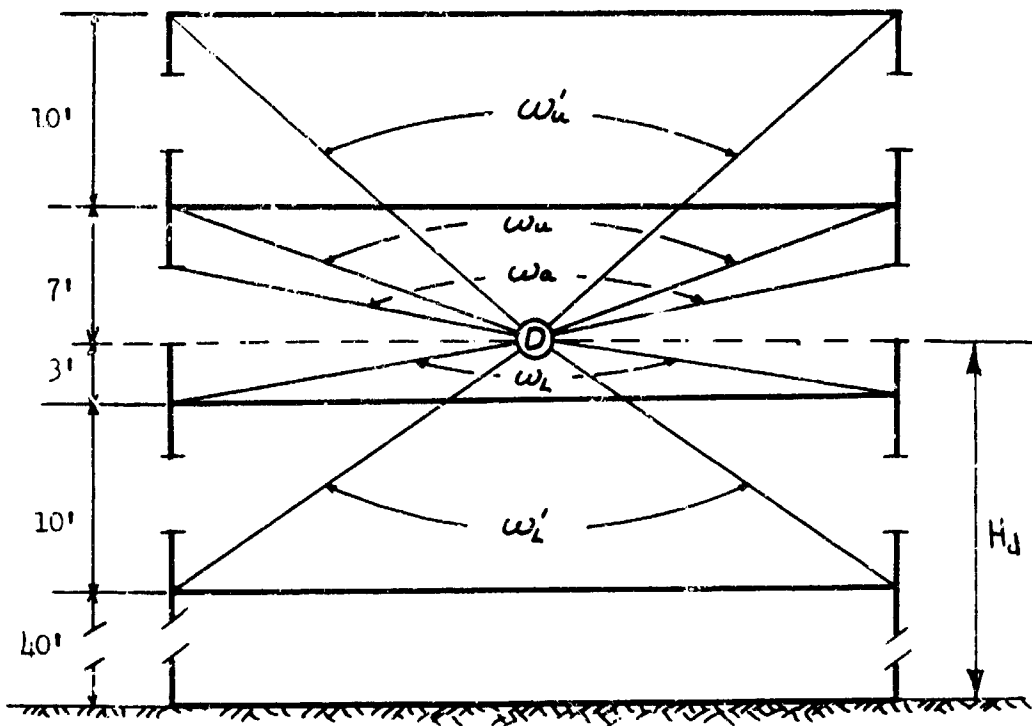


Figure 5.7

Given: Structure shown in Figure 5.7

Width = 75'

Length = 100'

Mass Thicknesses:  $X_o = 80\text{psf}$  all stories

$X'_o = 60\text{psf}$

$X_f = 60\text{psf}$

$X_o = 150\text{psf}$

Apertures 3' wide by 4' high on 6' centers. Sill height = 3' above floor.

This is the same structure used in Example 5.4 with the inclusion of apertures. The "score box" with  $w_a$  added is repeated here for convenience.

Example 5.7 (Continued)

	W	L	Z	e=W/L	n=2Z/L	$\omega$ Chart 3	$G_e$ Chart 5	$G_a$ Chart 5	$G_d$ Chart 6
$\omega_u$	75'	100'	17'	.75	.34	.68	.29	.072	---
$\omega_u$	75'	100'	7'	.75	.14	.85	.165	.045	---
$\omega_L$	75'	100'	3'	.75	.06	.93	.08	---	.04
$\omega_L$	75'	100'	13'	.75	.26	.73	.26	---	.32
$\omega_a$	75'	100'	4'	.75	.08	.91	.105	.029	---

$$S_w(X_e) = S_w(80\text{psf}) = .69 \quad (\text{Chart 7})$$

$$E(e) = E(.75) = 1.40 \quad (\text{Chart 8})$$

Ground Contribution:

a. Sixth story

Solid Wall Contribution

$$C_g = \left\{ \left[ G_d(\omega_L, H_d) + G_a(\omega_u) - P_a G_a(\omega_a) \right] \left[ 1 - S_w(X_e) \right] + \left[ G_s(\omega_L) + G_s(\omega_u) - P_a G_s(\omega_a) \right] S_w(X_e) E(e) \right\} B_e(X_e, H)$$

$$B_e(X_e, H) = B_e(80\text{psf}, 53') = .065 \quad (\text{Chart 2})$$

$$P_a \text{ for 3' window on 6' centers} = 3/6 = .5$$

$$C_g = \left[ (.04 + .045 - .5 \times .029)(1 - .69) + (.08 + .165 - .5 \times .105)(.69)(1.4) \right] (.065) = .0135$$

Aperture Contribution

$$C_g = P_a G_a(\omega_a) B_e(0, H)$$

$$B_e(0, H) = B_e(0, 53') = .50 \quad (\text{Chart 2})$$

$$C_g = (.5)(.029)(.5) = .0073$$

Total Ground contribution, sixth story = .0073 + .0135 = .0208

Example 5.7 (Continued)

b. Fifth story

Solid Wall Contribution

$$C_g = \{G_g B_e B_f\} (1-A_p)$$

$$A_p = \frac{\text{Area of Windows}}{\text{Area of Wall}} = \frac{3 \times 4}{6 \times 10} = .2$$

$$\{G_g B_e B_f\} = .00105 \quad (\text{Example 5.4})$$

$$C_g = \{.00105\} (1-.2) = \underline{.00084}$$

Aperture Contribution

$$C_g = [G_d(\omega_L, H_d) - G_d(\omega_L, H_d)] A_p B_e(0, H) B_f(X_f)$$

$$B_e(0, H) = B_e(0, 53') = .5$$

(Chart 2)

$$B_f(X_f) = B_f(60 \text{ psf}) = .062$$

$$C_g = (.32 - .04)(.20)(.52)(.062) = \underline{.00173}$$

$$\text{Total fifth story contribution} = .00084 + .00173 = .0026$$

c. Seventh story

Solid Wall Contribution

$$C_g = \{G_g B_e B_o'\} (1-A_p)$$

$$\{G_g B_e B_o'\} = .00034 \quad (\text{Example 5.4})$$

$$C_g = (.00029)(1-.2) = \underline{.00027}$$

Aperture Contribution

$$C_g = [G_a(\omega_u') - G_a(\omega_u)] A_p B_e(0, H) B_o'(X_o')$$

$$B_e(0, H) = B_e(0, 53') = .5$$

$$B_o'(X_o') = B_o'(60 \text{ psf}) = .045$$

$$C_g = (.072 - .045)(.2)(.5)(.045) = \underline{.00012}$$

$$\text{Total contribution, seventh story} = .00027 + .00012 = .00039$$

#### Example 5.7 (Continued)

d. Total Ground Contribution = .0208 + .0026 + .00039 = .0238

Roof Contribution: There is no change in the roof contribution from Example 5.4.

$$C_o = .0056$$

$$R_f = C_o + C_g = .0056 + .0238 = .0294$$

$$P_f = \frac{1}{R_f} = \frac{1}{.0294} = 34$$

Comparing this result with Example 5.4, the effect of the windows is to reduce the  $P_f$  from 42 to 34 or about 19%.

-----

### 5.9 PASSAGeways AND SHAFTS

Contribution through a horizontal passageway or vertical shaft can be calculated by the procedures discussed in these paragraphs; however, this calculation is frequently complicated by one or more turns in the passageway between the opening and the shelter area. When these turns exist, the contribution is first determined at a point common to the center lines of the first and second legs of the passageway. For subsequent changes of direction, the solid angle fractions are used directly as multipliers since the directional response in these cases is not well defined. Experimental results indicate that the solid angle fraction subtended by a detector in the second leg of an L-shaped corridor should be reduced by a factor of 0.2 to account for diffusion of the radiation as it scatters around the first right angle turn. In subsequent turns the solid angle fraction should be reduced by a factor of 0.5 (note that solid angle fraction 0.5 is a solid angle fraction of a sphere). Example 5.8 illustrates this procedure for one right angle turn. For the special case of the decontaminated skylight the contribution at point 1 is determined from Table 8.1b or can be computed from Chart 10 for a mass thickness of zero.

### 5.10 FICTITIOUS BUILDINGS

#### 5.10.1 GENERAL

The systems of analysis presented in this section are based on determining the response of a detector in a blockhouse symmetrical about the detector. For this reason, before the contribution through any section of a real building can be determined, that section must be incorporated into the walls or roof of a blockhouse symmetrical about the detector. These blockhouses are called fictitious buildings and are used extensively with this system of analysis. A fictitious building must:

# EXAMPLE 5.8

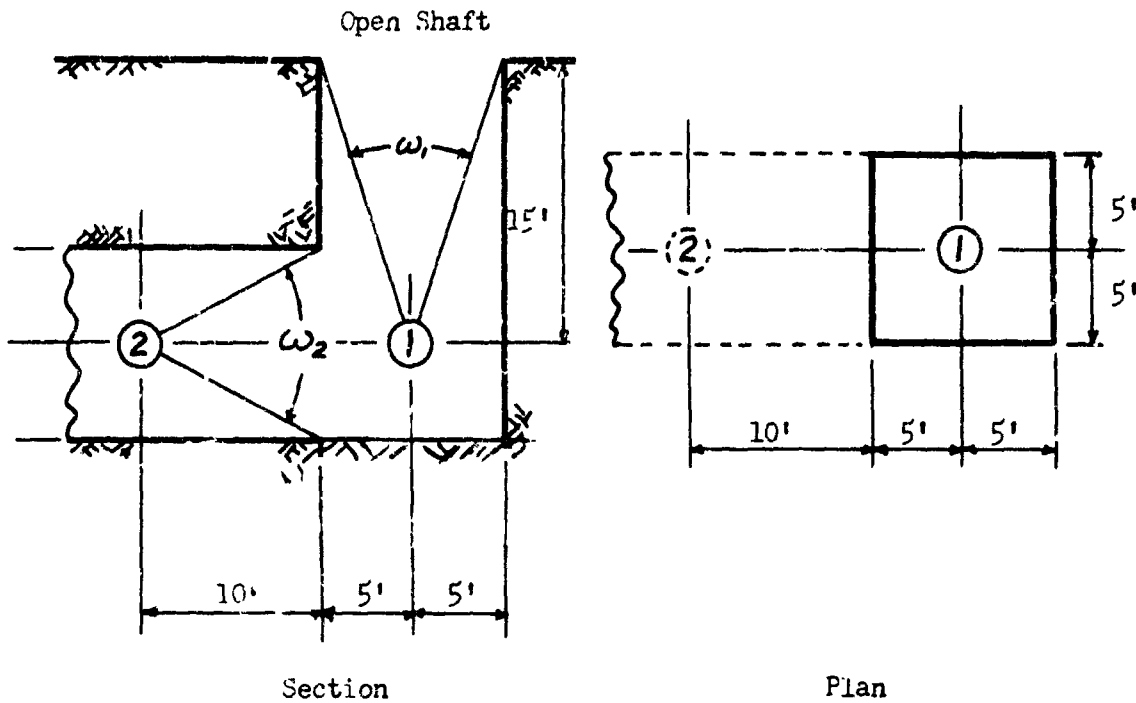


Figure 5.8

Given: Detector location in a mine as shown in Figure 5.8.

	W	L	Z	$\sigma = W/L$	$n = 2Z/L$	$\omega$
$\omega_1$	10	10	15	1.0	3.0	.06
$\omega_2$	10	10	10	1.0	2.0	.13

It is assumed the only radiation reaching point 2 comes through the open shaft. The contribution through the shaft opening is the same as that for a decontaminated skylight and may be obtained from Table 8.1..

$$R_{f2} = (R_{f1})(\omega_2)(.2)$$

$$R_{f1} = .0025 \text{ (Chart 10 for } \omega_1 = .06)$$

$$R_{f2} = (.0025)(.13)(.20) = .000065$$

$$P_f = \frac{1}{R_f} = \frac{1}{.000065} = 15,500$$



- a. Have the same type construction as the real section being analyzed.
- b. Be symmetrical about the detector.
- c. When superimposed over the actual building, coincide with the walls or roof being analyzed.

A simple procedure can be used to determine the size and shape of the fictitious buildings needed to analyze any section of a real building. If lines are drawn through the detector parallel to the exterior walls (or limits of the roof area), the perpendicular distances from these lines to the walls are the half lengths and half widths of the required fictitious buildings.

#### 5.10.2 ROOF CONTRIBUTIONS

There are four complications in roof problems which require the use of fictitious buildings:

- a. The mass thickness varies in different parts of the roof.
- b. The detector is unsymmetrically located.
- c. The roof symmetry is destroyed by interior partitions.
- d. Any combination of the above.

Example 5.9 illustrates the use of fictitious buildings for roof contributions. Notice that the contribution from each roof is found by creating a fictitious roof which includes the actual roof, subtracting a core contribution when appropriate, and then taking a proportional part (either  $1/4$ ,  $1/2$ , or  $3/4$ ) of the result.

#### 5.10.3 GROUND CONTRIBUTION

The first step in determining the ground contribution is to decide which sectors must be analyzed separately. When doing this, it is advisable to ignore minor variations in mass thickness and geometry. The separate sectors are then grouped so those with the same mass thickness and which may be included in one fictitious building, can be analyzed at the same time. If it is possible to include a wall as part of more than one fictitious building, the wall should be included in the fictitious building with the highest eccentricity ratio, that is, nearest to a square. Example 5.9 illustrates the use of fictitious buildings.

# EXAMPLE 5.9

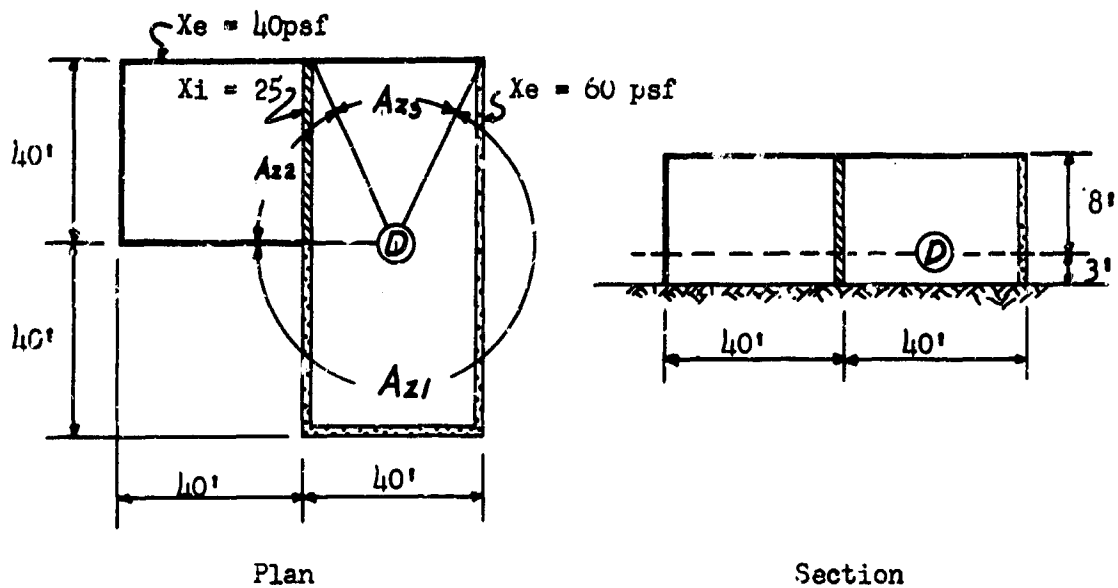


Figure 5.9a

Given: Off center detector location shown in Figure 5.9

Mass Thickness:  $X_o$  - shown in Figure 5.9

$X_o = 100$  psf

Ground Contribution:

Figures 5.9b and 5.9c illustrate the fictitious buildings required to determine the ground contribution. Azimuthal sector  $Az_3$ , has been included in building No. 2 to reduce the number of calculations.

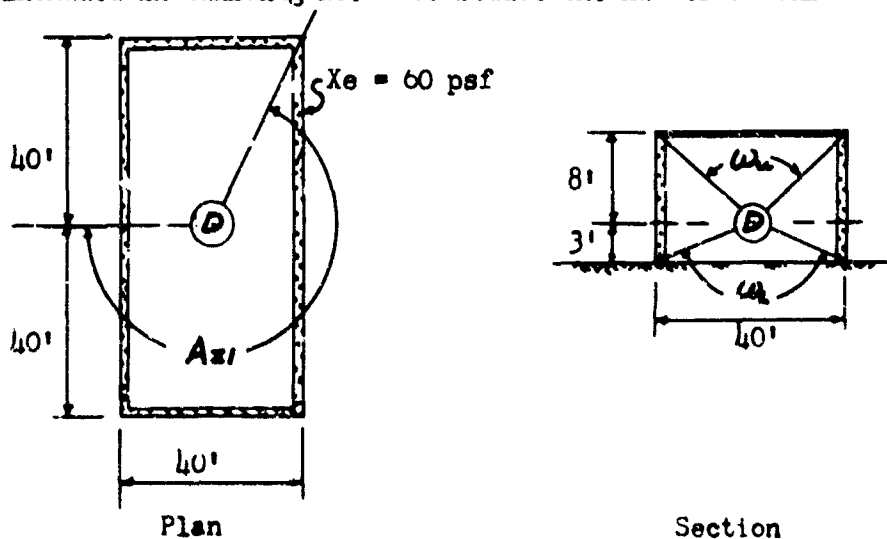


Figure 5.9b  
Fictitious building No. 1

# Example 5.9 (Continued)

## Fictitious Building No. 1

	W	L	Z	$e=W/L$	$r=2Z/L$	$\omega$ Chart .3	$G_s$ Chart 5	$G_a$ Chart 5	$G_d$ Chart 6
$\omega_u$	40	80	8'	.50	.20	.73	.26	.065	---
$\omega_L$	40	80	3'	.50	.075	.89	0.125	---	.43

$$S_w(X_e) = S_w(60\text{psf}) = .63 \quad (\text{Chart } 7)$$

$$E(e) = E(.50) = 1.34 \quad (\text{Chart } 8)$$

$$B_e(X_e, H) = B_e(60\text{psf}, 3') = .24 \quad (\text{Chart } 2)$$

$$A_{z1} = 243^\circ/360^\circ = .67$$

$$C_g = \{ [G_d(\omega_L, H_d) + G_a(\omega_u)] [1 - S_w(X_e)] + [G_s(\omega_L) + G_s(\omega_u)] S_w(X_e) E(e) \} B_e(X_e, H) A_z$$

$$= [(.43 + .065)(1 - .63) + (.125 + .26)(.63)(1.34)] (.24)(.67) = .081$$

.....

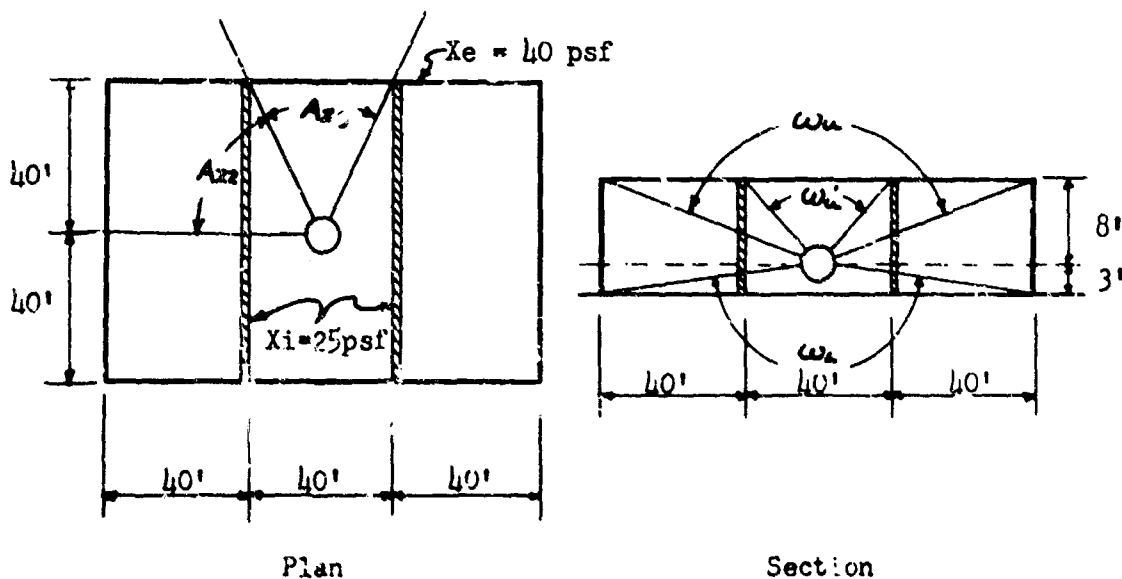


Figure 5.9c  
Fictitious Building No. 2

Example 5.9 (Continued)

Fictitious Building No. 2:

	W	L	Z	e=W/L	m=2Z/L	Chart 3	Chart 5	Chart 5	Chart 6
$\omega_u$	80	120	8'	.67	.133	0.85	.165	.044	---
$\omega_L$	80	120	3'	.67	.05	.94	.072	---	.30

$$S_w(X_o) = S_w(40\text{psf}) = .53 \quad (\text{Chart } 7)$$

$$E(e) = E(.67) = 1.38 \quad (\text{Chart } 3)$$

$$B_o(X_o, H) = B_o(40\text{psf}, 3') = .37 \quad (\text{Chart } 2)$$

$$B_1(X_1, 3') = B_1(25\text{psf}, 3') = .55 \quad (\text{Chart } 2)$$

$$A_{z2} = 63^\circ/360^\circ = .18 \quad A_{z3} = 53^\circ/360^\circ = .15$$

In this fictitious building sectors  $A_{z3}$  and  $A_{z2}$  differ only by the barrier factor  $B_1(25\text{psf}, 3')$ . These two sectors are combined in the functional expression:

$$C_g = \left\{ [G_u(\omega_L, \omega_d) + G_u(\omega_u)] (1 - S_w(X_o)) + [G_s(\omega_L) + G_s(\omega_u)] S_w(X_o) E(e) B_o(X_o, H) \right. \\ \left. [A_{z3} + A_{z2} B_1(X_1, 3')] \right\} \\ = \{ (.30 + .044)(1 - .53) + (.072 + .165)(.53)(1.38) \} (.37) [.15 + (.18)(.55)] = .031$$

$$\text{Total Ground Contribution} = .031 + .078 = .109$$

Roof Contribution: The roof plan of fictitious building No. 2 is used to determine the roof contribution. The solid angle fractions involved are shown in the figure also.

$$C_o = C_o(\omega_u', X_o) + \frac{[C_o(\omega_u, X_o) - C_o(\omega_u', X_o)]}{L} B_1'(X_1')$$

$$= C_o(.73, 100 \text{ psf}) + \frac{[C_o(.85, 100 \text{ psf}) - C_o(.73, 100 \text{ psf})]}{L} B_1'(25 \text{ psf})$$

$$= .02 + \left[ \frac{.02 - .02}{L} \right] (.39) = .02$$

$$R_f = .02 + .109 = .13$$

$$P_f = 1/.13 = \underline{\underline{7.7}} \text{ or } \underline{\underline{8}}$$

#### 5.10.4 SMALL SECTOR ANALYSIS

When the azimuthal sector is small, the detector can be considered at the center of a large fictitious cylinder. This allows direct computation of the solid angle fractions as described in paragraph 3.4.2. This procedure is especially applicable for isolated windows and doorways; but may also be used for short segments of wall. The shape factor E for a circular building is 1.57.

Example 5.10 illustrates this procedure.

#### 5.11 MUTUAL SHIELDING

##### 5.11.1 GENERAL

When an adjacent structure limits the width of contaminated plane on one side of a shelter, the amount of radiation incident on that side will be reduced, with a corresponding reduction in the contribution through that wall. Two adjacent structures tend to mutually shield one another, hence the term "mutual shielding"; although, "limited field of contamination" might be a more descriptive term.

When analyzing a structure with mutual shielding it is necessary to treat wall-scattered and non-wall-scatter components separately and to make some simplifying assumptions regarding the extent of the contaminated plane.

##### 5.11.2 WALL-SCATTERED COMPONENT

A mutually shielded wall sees a contaminated plane of finite width. In some cases, such as an enclosed courtyard, the contaminated plane is well defined and the analysis may proceed directly; however, in the majority of cases it is necessary to impose artificial limitations on the contaminated plane. This is done by assuming the width of field equal to the actual width,  $W_c$ . The length of field is taken as the length of the building plus twice the width of field. This is shown in Figure 5.12.

This effect is considered for wall-scattered radiation by using a reduced barrier factor,  $B_{ws}$ , instead of the usual  $B_o$ .  $B_{ws}$  is determined by finding the solid angle fraction,  $\omega_s$ , subtended by the finite plane at the mid point of the wall under study. This is shown in Figure 5.12. Note that  $\omega_s$  is a solid angle fraction at a point above the edge of a plane. For this reason the plane must be doubled and the solid angle fraction  $2\omega_s$  determined. Then  $\omega_s = \frac{2\omega_s}{2}$ . With this solid angle fraction and the mass

thickness of the wall,  $B_{ws}(\omega_s, X_o)$  can be read from Chart 9. No

# EXAMPLE 5.10

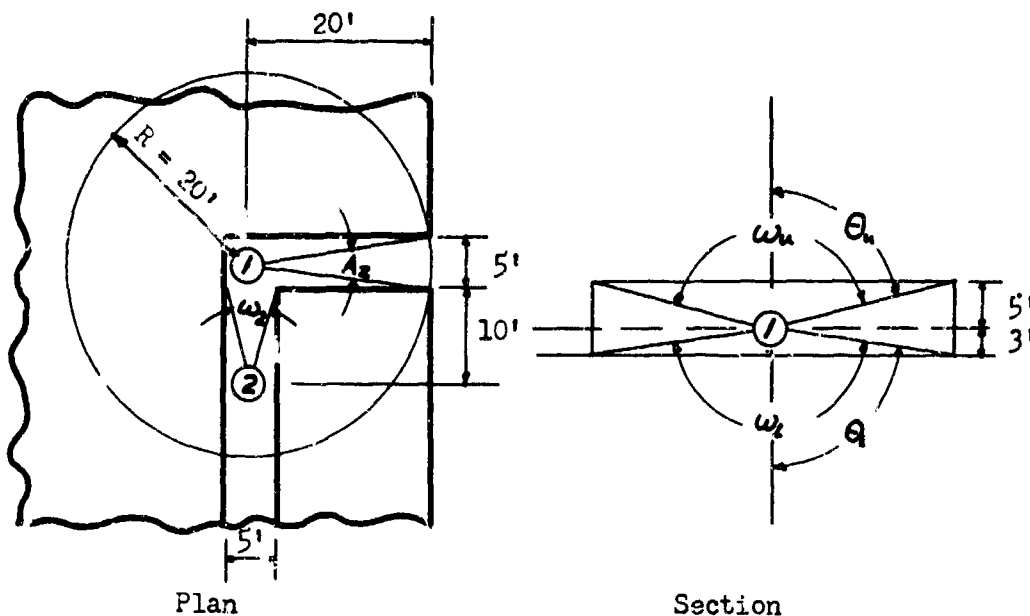


Figure 5.10

It is assumed the only radiation reaching the detector is that coming down the passageway from the opening beyond point 1.

	W	L	Z	$\phi$	$\cos \theta$	e	n	$\omega^*$	$G_a$	$G_d$
$\omega_2$	5'	8'	10'	---	---	.625	2.5	.053	---	---
$\omega_u$	R=20'		5'	76°	.24	---	---	.76	.06	---
$\omega_L$	R=20'		3'	81.5°	.15	---	---	.85	---	.50

\* A cylindrical fictitious building is used to determine  $R_{f1}$ . For a cylindrical section  $\omega = 1 - \cos \theta$

$$R_{f1} = [G_d(\omega_L, H_d) + G_a(\omega_u)] B_\theta(0, H) A_z$$

$$B_\theta(0, H) = B_\theta(0, 3') = 1.0$$

$$A_z = 14^\circ / 360^\circ = .039$$

$$R_{f1} = (.50 + .6)(1.0)(.039) = .022$$

$$R_{f2} = R_{f1}(\omega_2)(.2) = (.022)(.053)(.2) = .00023$$

$$P_f = \frac{1}{R_f} = \frac{1}{.00023} = 4300$$

other change is required in finding the wall-scattered component. Thus, the functional expression for wall-scattered radiation for the shielded sector of the second story wall in Figure 5.11 is:

$$G_g(\text{shielded}) = [G_s(\omega_u) + G_s(\omega_L)] S_w(X_e) E(e) B_{ws}(\omega_s, X_e) A_z(\text{shielded})$$

A new value of  $B_{ws}$  must be computed for each story, as shown in Figure 5.11a.

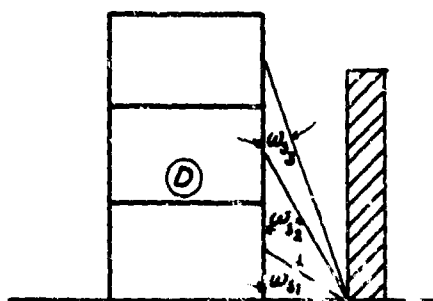


Figure 5.11a

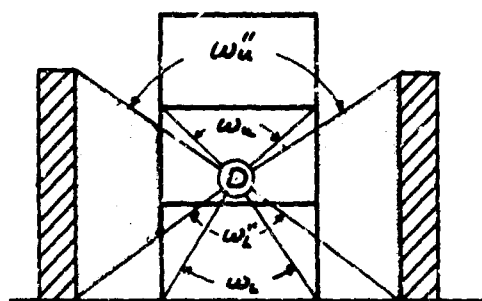


Figure 5.11b

Figure 5.11 Effect of Mutual Shielding

### 5.11.3 NON-WALL-SCATTERED COMPONENT

Figure 5.11b illustrates the effect of mutual shielding on non-wall-scattered radiation. This effect can be considered by the differencing technique discussed in paragraph 5.2. The non-wall-scattered radiation originating beyond the shield and which thereby is not received by the detector is subtracted from that originating from an infinite field. Thus  $G_d(\omega_L, H_d) - G_d(\omega_L'', H_d)$  is the ground direct component, non-wall-scattered radiation. In the particular case of Example 5.11, the detector story is shielded from all ground direct radiation. For mutually shielded buildings, the full value of  $G_d(\omega_L)$  is used even though it appears that part of skyshine is blocked out by the adjacent building. This is done because the skyshine term includes other scattering contributions. Thus the ceiling-shine contribution is not affected much by the mutual shield and the scattering from the adjacent building increases as the  $\omega_c$  distance decreases. Since the actual magnitude of these various scattering components is not known, the full value of  $G_d$  is used.

The solid angle fraction  $\omega_u''$  and  $\omega_L''$  should be computed based on the shape and dimensions of the building. The Z distance is determined by drawing a ray from the detector to the mutual shield. The vertical distance between the interception of the ray with the exterior wall and the detector is the required value of Z.

Example 5.11 illustrates the effect of mutual shielding.

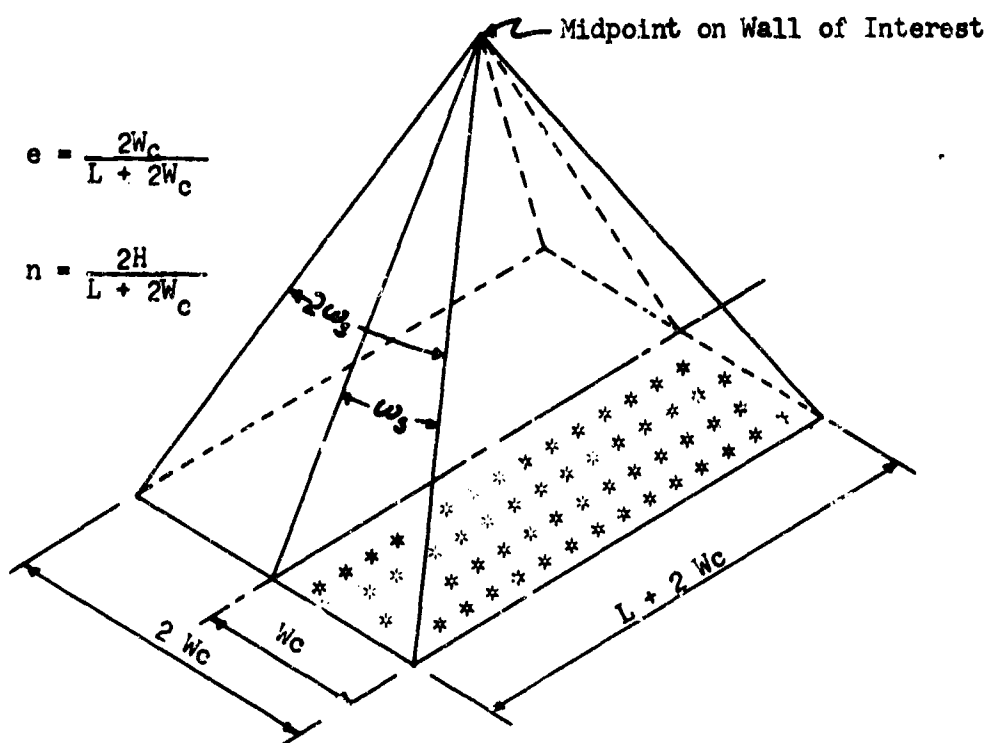


Figure 5.12 Computation of Solid Angle Fraction for a Limited Strip

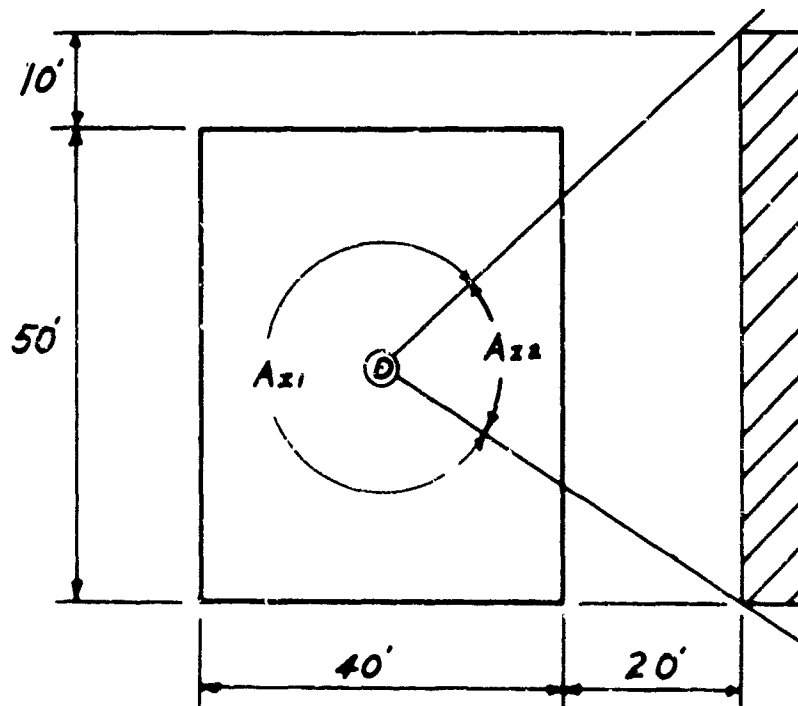
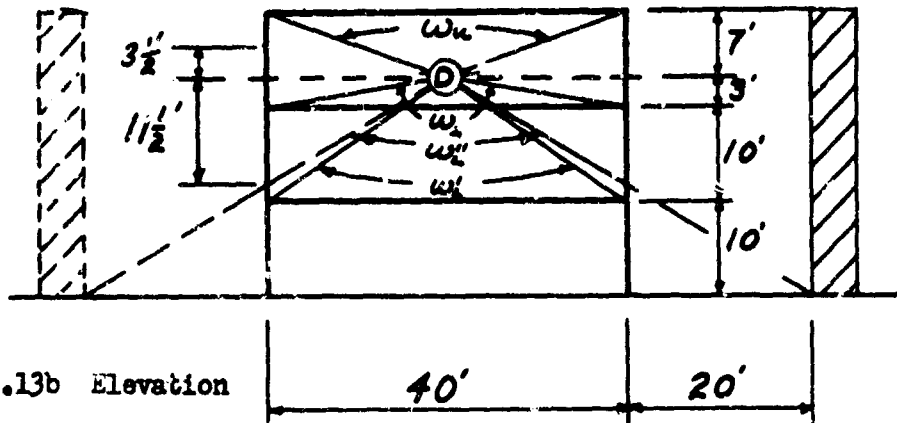


Figure 5.13a Plan



### EXAMPLE 5.11



**Figure 5.13b Elevation**

Given: Structure shown in Figure 5.13

Mass Thicknesses:  $X_0 = 60\text{paf}$

$$X_0 = 1.00 \text{ psf}$$

	W	L	Z	$\sigma=W/L$	$n=2Z/L$	$\omega$ Chart 3	$G_s$ Chart 5	$G_a$ Chart 5	$G_d$ Chart 6
$\omega_u$	40	50	7	.80	.28	.72	.27	.066	—
$\omega_L$	40	50	3	.80	.12	.88	.135	—	.19
$\omega_L^I$	40	50	13	.80	.52	.54	.36	—	.60
$\omega_L^{II}$	40	50	11.2	.80	.46	.58	—	—	.56
$\omega_{s3}$	40	90	25	.44	.55	.36/2 = .18	—	—	—
$\omega_{s2}$	40	90	15	.44	.33	.54/2 = .27	—	—	—

$$S_v(x_o) = S_v(60\text{psf}) = .63 \quad (\text{Chart } 7)$$

$$E(\bullet) = E(.80) = 1.40 \quad (\text{Chart } 8)$$

Ground Contribution:

a. Third story, unshielded

Example 5.11 (Continued)

$$C_g = \left\{ \left[ G_d(\omega_L, H_d) + G_a(\omega_u) \right] \left[ 1 - S_w(X_e) \right] + \left[ G_s(\omega_L) + G_s(\omega_u) \right] S_w(X_e) E(\bullet) \right\} B_e(X_e, H) A_{z1}$$

$$B_e(X_e, H) = B_e(60 \text{ paf}, 23') = .14 \quad (\text{Chart } 2)$$

$$A_{z1} = 287^\circ / 360^\circ = .80$$

$$C_g = \left\{ (.19 + .066)(1-.63) + (.135 + .27)(.63)(1.40) \right\} (.14)(.80) = .051$$

b. Third story, shielded. For this sector the wall-scattered and non-wall-scattered components are found separately. For the non-wall-scattered component the full value of skyshine is used as explained in paragraph 5.11.3 Non-Wall-Scattered Component. For the wall-scattered component, a reduced barrier reduction factor,  $B_{ws}(\omega_s, X_e)$ , is used which considers the size of the finite field.

Non-wall-scattered

$$C_g = \left[ G_a(\omega_u) \right] \times \left[ 1 - S_w(X_e) \right] B_e(X_e, H) A_{z2}$$

$$A_{z2} = 73^\circ / 360^\circ = .20$$

$$C_g = (.066) (1-.63)(.14)(.20) = \underline{.00068}$$

Wall-scattered

$$C_g = \left[ G_s(\omega_L) + G_s(\omega_u) \right] S_w(X_e) E(\bullet) B_{ws}(\omega_s, X_e) A_{z2}$$

$$B_{ws}(\omega_s, X_e) = B_{ws}(.18, 60 \text{ paf}) = .0074 \quad (\text{Chart } 9)$$

$$C_g = (.135 + .27)(.62)(1.40)(.006) .2 = .00053$$

$$\text{Total third story} = .051 + .00068 + .00053 = .0522 \text{ or } \underline{.052}$$

c. Second story, unshielded

$$C_g = \left\{ \left[ G_d(\omega_L, H_d) - G_d(\omega_L, H_d) \right] \left[ 1 - S_w(X_e) \right] + \left[ G_s(\omega_L) - G_s(\omega_L) \right] S_w(X_e) E(\bullet) \right\} \times B_e(X_e, H) B_f(X_f) A_{z1}$$

$$B_e(X_e, H) = B_e(60 \text{ paf}, 23') = .14 \quad (\text{Chart } 2)$$

$$B_f(X_f) = B_f(40 \text{ paf}) = .11 \quad (\text{Chart } 1)$$

$$C_g = \left\{ (.60 - .19)(1-.63) + (.36 - .135)(.63)(1.40) \right\} (.14)(.11)(.8) = \underline{.0043}$$

Example 5.11 (Continued)

d. Second story shielded

Non-Wall-Scattered

$$C_g = [G_d(\omega_L', H_d) - G_d(\omega_L'', H_d)] [1 - S_w(X_e)] B_e(X_e, H) R_f(X_f) A_{z2}$$

$$= (.60 - .56)(1 - .63)(.14)(.11)(.2) = \underline{.000045}$$

Wall Scattered

$$C_g = [G_s(\omega_L') - G_s(\omega_L'')] S_w(X_e) E(e) B_{ws}(\omega_s, X_e) R_f(X_f) A_{z2}$$

$$B_{ws}(\omega_s, X_e) = B_{ws}(.27, 60 \text{psf}) = 0.017 \quad (\text{Chart. 9})$$

$$C_g = (.36 - .135)(.63)(1.4)(0.017)(.11)(.2) = \underline{.000074}$$

$$\text{Total, second story} = .0043 + .000045 + .00007 = \underline{.0044}$$

The effect of the mutual shield is seen by comparing the third story ground contribution through the shielded sector with and without the shield.

With Shield  
.0011

Without Shield  
.013

$$\text{Total ground contribution} = .0044 + .052 = .056$$

Roof Contribution:

$$X_o = 100 \text{psf } \omega_u = .72$$

$$C_o = C_o(\omega_u, X_o) = C_o(.72, 100 \text{psf}) = \underline{.02}$$

$$R_f = C_o + C_g = .056 + .02 = .076$$

$$F_f = \frac{1}{R_f} = \frac{1}{.076} = \underline{13}$$

## CHAPTER 6

### DETAILED PROCEDURE - COMPLEX APPLICATIONS

#### 6.1 INTRODUCTION

The type problems discussed in Chapter 5, although long in some cases, were nevertheless variations on the basic block house and required little imagination in their analysis.

All structures do not fit so well into this pattern; the analyst may be required to make approximations or assumptions before proceeding with the analysis. The purpose of this Chapter is to provide an aid in making these approximations.

#### 6.2 ROOF CONTRIBUTIONS

##### 6.2.1 VARIATIONS IN MASS THICKNESS

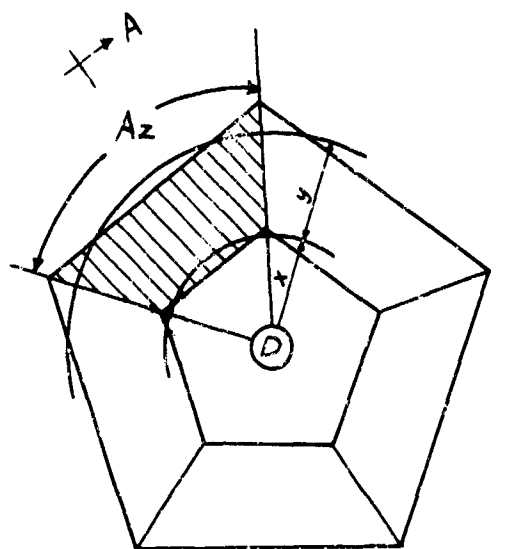
In many types of roof and floor construction the joists are closely spaced and thereby add significantly to the mass thickness of the barrier. In such cases the joists may be "smeared" over the total area. This is done by finding the total weight of the roof plus the joists and dividing by the area of the roof. A similar procedure was used in determining the mass thickness for hollow concrete blocks given in Table 4.2.

##### 6.2.2 SLOPING ROOFS

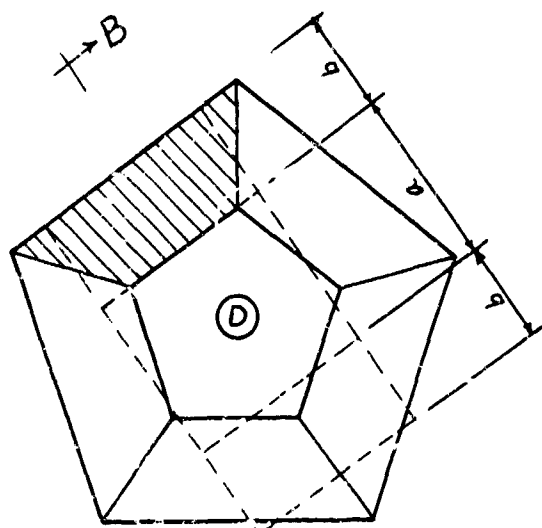
Roofs composed of sloping components (gables, hip roofs, etc.) cannot be analyzed as such but must be converted to an equivalent flat roof. This may be done by using the horizontal projection of the actual roof at an elevation equal to the center of gravity of a vertical section through the roof. The fallout is then assumed to be uniformly distributed over the horizontal projection.

##### 6.2.3 IRREGULAR SHAPED ROOFS

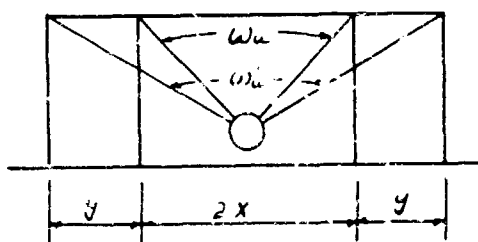
The existence of unevenly spaced partitions may divide a roof into irregular segments which cannot readily be included in a fictitious shape. Further, many modern buildings are not rectangular in shape. In such situations it is necessary to approximate the roof shape by a circular or rectangular roof which can then be analyzed. Figure 6.1 illustrates approximations. A general rule to be followed in making such approximations is to treat the largest sources of contribution as accurately as possible. Lesser contributions, as from peripheral roof areas, may then be treated by approximation with little loss of accuracy.



Plan A

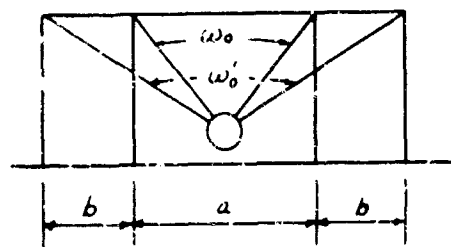


Plan B



Section A-A

$$C_o = \left[ C_o(\omega'_u, X_o) - C_o(\omega_u, X_o) \right] A_s^*$$



Section B-B

$$C_o = \left[ C_o(\omega'_o, X_o) - C_o(\omega_o, X_o) \right]$$

\* Azimuthal sectors may be used with circular roots only.

Figure 6.1 Approximating Roof Shapes

#### 6.2.4 MULTI-LEVEL ROOFS

Multi-level roofs are analyzed as a series of separate roof problems. Each section of roof is considered as part of a fictitious roof at that level and analyzed as such. Figure 6.2 illustrates this procedure for a two level roof.

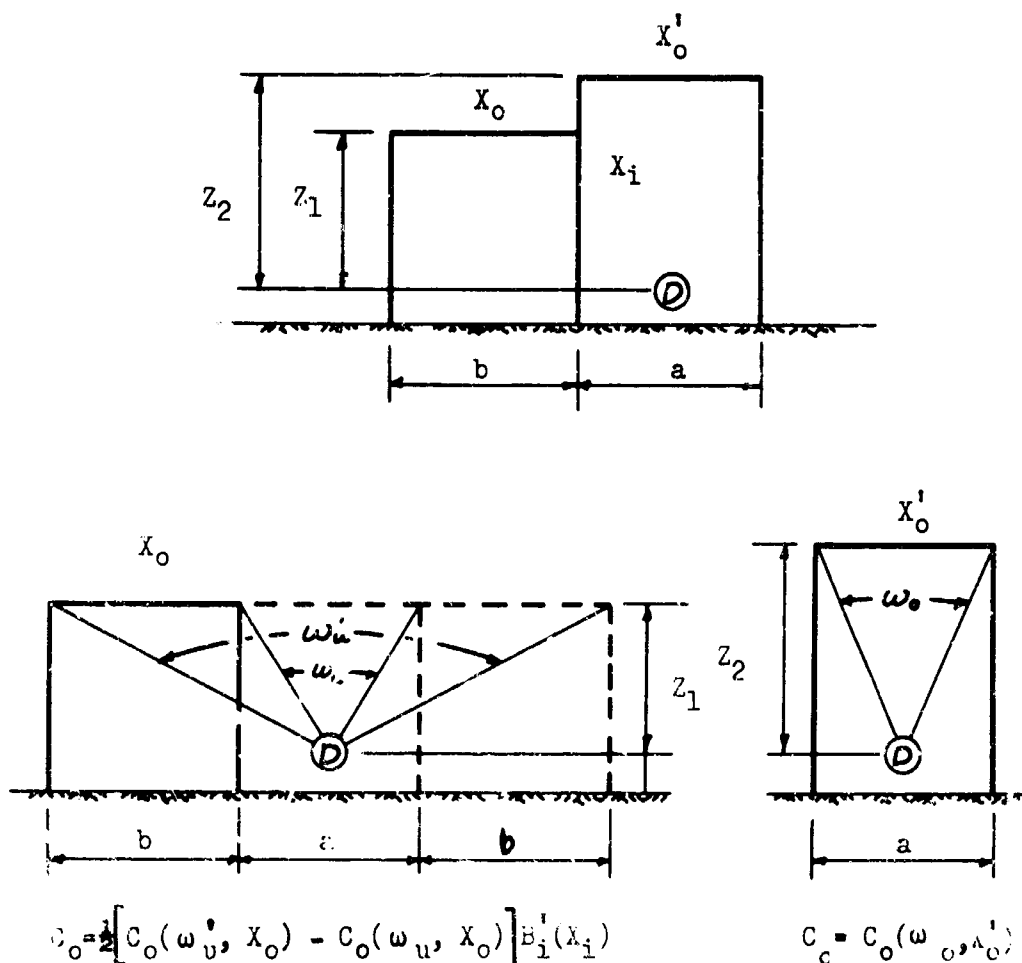


Figure 6.2 Multi-level Roof

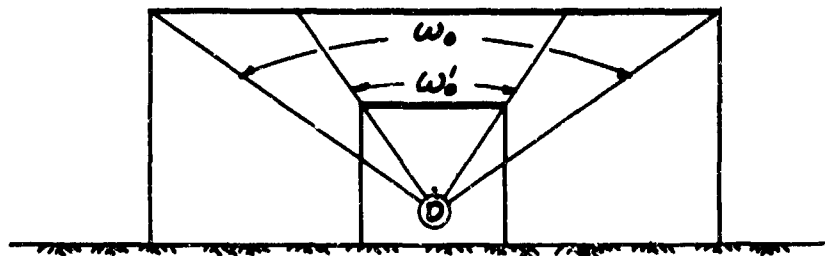
#### 6.2.5 DISCONTINUOUS BARRIERS

Horizontally discontinuous barriers are analyzed using azimuthal sectors as discussed in Chapter 5. When barriers are discontinuous in the vertical direction, this discontinuity may be considered by using solid angle fractions and the basic assumption that all radiation travels to the detector in a straight line from the exterior contributing surface.

Figure 6.3 illustrates this procedure.

$X_0$  = Mass thickness of uppermost roof only

$X'_0$  = Combined mass thickness of both horizontal barriers



$$C_0 = C_0(\omega'_0, X'_0) + [C_0(\omega_0, X_0) - C_0(\omega'_0, X_0)] B_1^1(X_1)$$

Figure 6.3 Vertically Discontinuous Barriers

All radiation originating within the limits of  $\omega'_0$  is assumed to pass through the intermediate horizontal barrier while all roof contribution outside of  $\omega'_0$  passes through the interior partition.

### 6.3 GROUND CONTRIBUTIONS

#### 6.3.1 IRREGULAR SHAPES

Most irregularly shaped structures may be analyzed using fictitious buildings and azimuthal sectors as discussed in Chapter 5. When a structure is of such a shape that it cannot be conveniently fitted into a fictitious building its shape may be approximated by a rectangular or circular structure, similar to the method used for roofs in Figure 6.1.

#### 6.3.2 SETBACKS

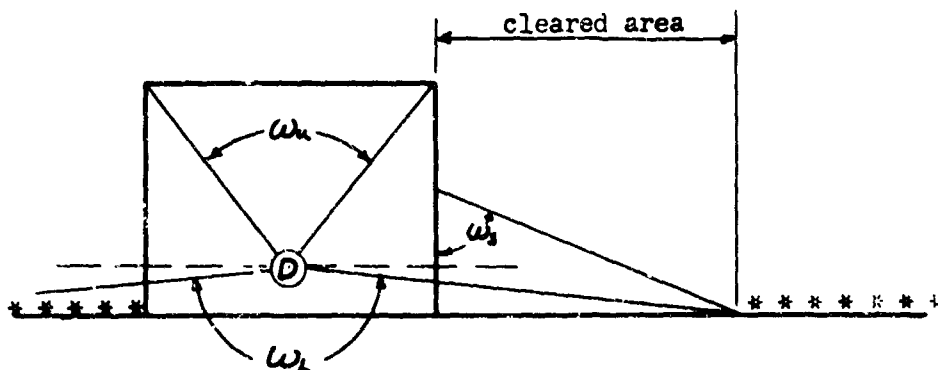
The analysis of a setback depends on its height relative to the surrounding ground. A low level setback should be analyzed as if it were a semi-infinite plane, due to the importance of the radiation originating beyond the setback. At higher levels this ground radiation is of less importance and the setback can be considered a finite contaminated plane, that is, a mutual shielding problem. However, the ground contribution must also be determined. No fixed height can be given to distinguish between a high-level and a low-level setback, this will depend on the nature of the surrounding ground, the existence of other setbacks,

adjacent buildings, and in general, familiarity and working knowledge of the shelter analyst with the analysis procedure.

### 6.3.3 CLEARED AREAS

When fallout is deposited on the surface of a river, lake, or other body of water, it sinks and its radiation is thus attenuated by the barrier effect of the water. For this reason a body of water may be analyzed as a cleared area.

If a cleared area is some distance from the structure it may be considered by applying the factor illustrated in paragraph 7.10 to the ground contribution. Areas immediately adjacent to the structure will have a more pronounced effect on the reduction factor and may be analyzed as the opposite of mutual shielding. The geometry and barrier effects of such a case are illustrated in Figure 6.4.



$$\text{Non-wall-scattered: Skyshine} = G_s(\omega_u) [1 - S_w(X_e)] B_e(X_e, H)$$

$$\text{Ground Direct} = G_d(\omega_L, H_d) [1 - S_w(X_e)] B_e(X_e, H)$$

$$\text{Wall-scattered} = [G_s(\omega_L) + G_s(\omega_u)] S_w(X_e) [B_e(X_e, H) - F_{ws}(\omega_s, X_e)] E(e)$$

Figure 6.4. Cleared Area

### 6.3.4 SLOPING GROUND

As sloping ground is a departure from THE STANDARD, it will have some effect on the reduction factor. When the slope is gentle and uniform this effect will be small and can be ignored. When the slope is non-uniform, downward, the ground tends to shield itself. In this case, the slope may be ignored or in extreme cases treated as a setback (see para 6.3.2).



A steep slope, upward away from the detector, can have a pronounced effect on the reduction factor, as ground direct radiation can now originate above the detector plane. Such a slope can be analyzed by treating it as the plane of reference instead of the horizontal plane. Figure 6.5 illustrates a procedure for doing this. Notice that the relation between the detector and the contaminated plane remains constant. The ground direct component can now be determined as a function of  $\omega_L$ ,  $\omega_L'$  and  $H_d$ .

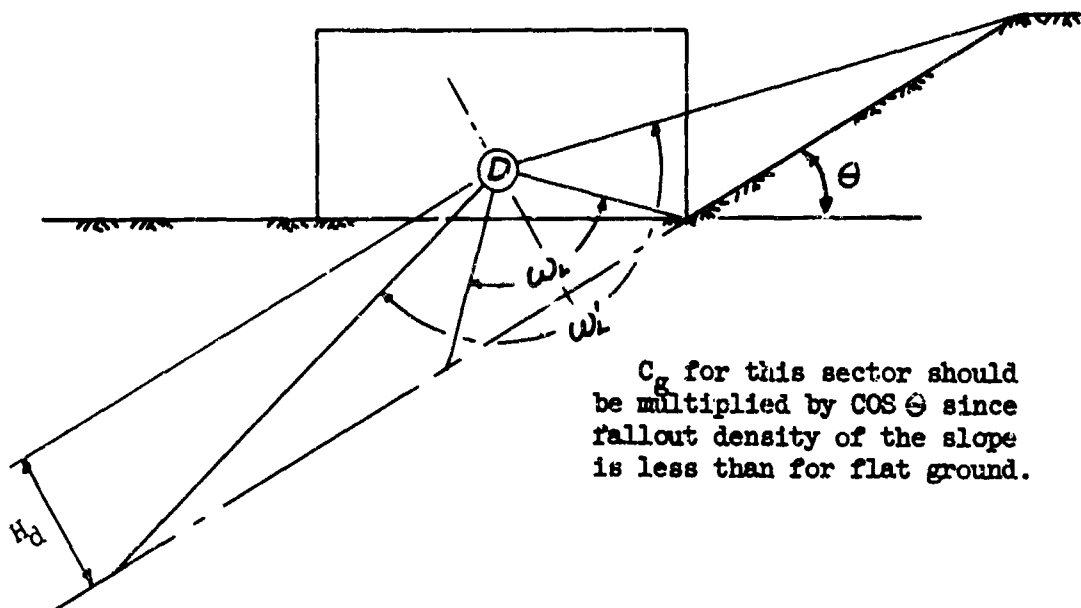


Figure 6.5 Slicing Contaminated Plane

#### 6.3.5 GROUND ROUGHNESS

The effect of ground roughness is to place an additional barrier between the detector and the radiating source. Unfortunately, little experimental data is available on this effect; however, by coupling available data with theory, a judgment can be made concerning its influence on the reduction factor.

Table 6.1 is the result of this judgment, wherein ground roughness is expressed in terms of an equivalent height of air. This fictitious height should be added to the value of  $H$  used in determining the exterior wall barrier reduction factor. This fictitious height is not added to  $H_d$  in the determination of  $G_d$ .

#### 6.3.6 PARTICLE PILE-UP

Particles of fallout which have been deposited on turfed areas do not tend to drift, and can be considered to remain uniformly

Table 6.1

## FICTITIOUS HEIGHTS FOR VARIOUS GROUND ROUGHNESS CONDITIONS

<u>Description</u>	<u>Fictitious Height* (feet)</u>
Smooth Plane	0
Paved Areas	0 - 5
Lawns	5 - 10
Gravelled Areas	10 - 20
Ordinary Plowed Field	20 - 40
Deeply Plowed	40 - 60

\* To add to actual value of H for use with wall-barrier curves, Chart 2.

distributed over the area. Field experiments indicate that depositions on paved areas are not so stable. A building located in a parking lot could be expected to have a "pile-up" of fall-out particles on its windward side. To estimate the influence of this pile-up on a protection factor, it is necessary to know its relative source concentration. This concentration can be related to the effective "fetch",  $F_e$ , of the paved area, that is the distance to the outer edge of the pavement from the wall of the building.

The effects of pile-up can be approximated by the following variation of the mutual shielding problem. Assume a finite contaminated strip of 10 feet wide, ( $M_c$ ). Make the normal calculations for mutual shielding for this strip; however, multiply the ground contribution by the ratio of fetch to contaminated strip,  $F_e/M_c$ .

For detector positions above the third floor the effect of pile-up will be small and can safely be ignored.

For a basement detector position, the contribution from pile-up through the earth adjacent to the basement wall may be of interest. This contribution can be approximated by the following expression (refer also to Figure 6.1):

$$C_g = \frac{120(1-\omega)(2-\omega) B_0(M_e, 3') F_e A_e}{UZ}$$

UZ

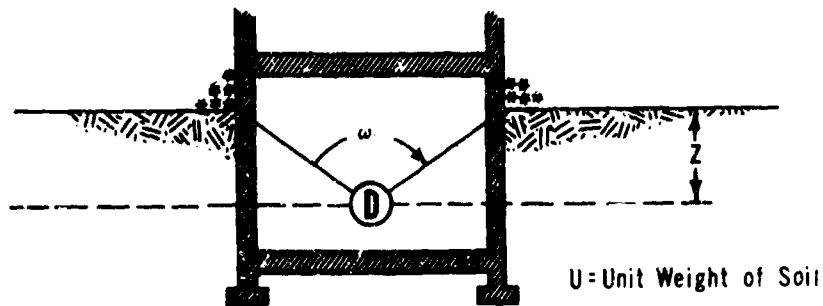


Figure 6.6 Particle Pile Up

This expression only provides the contribution through the lip of the earth surrounding the structure; contribution through the walls of the structure should be analyzed by the normal procedures.

## CHAPTER 7

### SIMPLIFIED, APPROXIMATE PROCEDURES

The Detailed Procedure presented in the preceding chapters is concise, consistent with accuracy; however, it is unwieldy and too time consuming for initial planning and design purposes. Several simplified approximate procedures have been developed which greatly reduce the time required for computations. These procedures, however, have varying degrees of accuracy when compared with the calculations derived by the Detailed Procedure. It may become necessary to verify all or part of the calculations on the final design by means of the Detailed Procedure.

The following publications are being used to illustrate the Simplified Approximate Procedure:

1. Shelter Design & Analysis, Volume 2, TR-20 Equivalent Building Method.
2. Protection Factor Estimator TM 64-1.

Example problems and methods of solution can be found in each of the publications.

## CHAPTER 8 RADIATION SHIELDING MODIFICATIONS

### 8.1 INTRODUCTION

#### 8.1.1 OBJECTIVES

The objective of shielding modification is to provide a desired degree of protection at minimum cost commensurate with shelter requirements. Maximum use must be made of existing structure properties to achieve this goal. Alternative designs and construction materials which provide greatest shielding must be used in new construction. A working knowledge of the systems of analysis and parameters of shielding is essential. Familiarity with building construction and design is also necessary. This Chapter reviews the parameters of shielding and applies the results to sample shielding modification situations.

#### 8.1.2 THEORY

The theory behind effective shielding modification is the system of shielding analysis presented in Chapter 6. This system is analyzed in detail to provide a qualitative estimate of the effectiveness of the various parameters of shielding in reducing radiation received. Means of varying these parameters in existing or planned construction are discussed and a general modification procedure is developed. This procedure is applied to sample situations and possible solutions for these particular examples are illustrated.

### 8.2 OVERHEAD CONTRIBUTION

#### 8.2.1 REDUCTION BY DECONTAMINATION

##### 8.2.1.1 Reduction Possible

Table 8.1 Skyshine Contribution through Decontaminated Roofs

Table 8.1a	
Skyshine Contribution Through Decontaminated Roofs	
Overhead Mass Thickness $X_o$ , psf	Skyshine Factor *
0	Use Table 8.1b
25	0.10
50	0.08
100	0.04
200	0.01

\* To be applied as a correction factor to values obtained from Chart 4

Table 8.1b			
Skyshine Contribution Decontaminated Roof of Zero Mass Thickness			
Solid Angle Fraction	Skyshine Contribution	Solid Angle Fraction	Skyshine Contribution
0.02	0.0008	0.20	0.0088
0.04	0.0016	0.40	0.019
0.06	0.0025	0.60	0.030
0.08	0.0038	0.80	0.048
0.10	0.0042	1.00	0.100

Complete decontamination can provide extreme reduction in the overhead contribution by eliminating the direct radiation and the skyshine originating from the contamination on the roof. The approximate results of complete decontamination of the roof area may be determined by comparing the skyshine component with the total overhead contribution. Table 8.1 lists the fractional portion of the overhead contribution determined from chart 4 represented by the skyshine component. For example, when  $X_0 = 100$  psf, skyshine is 4% of the total overhead contribution. A decontaminated roof with  $X_0 = 100$  and  $\omega_0 = .40(C_0(\omega_0, X_0) = .016)$  would have a contribution  $= .04 \times .016 = .00064$ . It should be noted that skyshine is a larger portion of the contribution for a lighter roof, and that the skyshine originating from the radiation on the roof itself is an increasing portion of the whole with larger and higher roofs. Thus, complete decontamination can provide a large reduction in the overhead contribution.

#### 8.2.1.2 Decontamination Methods

The principle remote operated systems which may be employed for roof decontamination are:

- a. Roof Washdown System - In principle, this system covers the roof with a rapidly moving film of water to loosen, propel, dissolve, or suspend the fallout. A closed system required water distribution, collection, storage, settling, filtration, and pumping. A "once-through" system requires water supply, pumping, collection, and disposal. The effectiveness of the system is principally dependent on the water flow and coverage, and the slope and composition of the roof surface. Washing effectiveness test results for various roof surfaces and slopes are illustrated in Table 8.2 (from Reference 1. RADIOLOGICAL PROTECTIVE CONSTRUCTION, USNRDL, 467, 1962).

Table 8.2 - Influence of Roughness and Slope on Roof Washdown Effectiveness

Slope	FRACTION REMAINING		
	Masonite (1.8 gpm/ft)	Roll Roofing (2.7 gpm/ft)	Composition Shingles (2.7 gpm/ft)
1:4	.004	.022	.083
1:12	.016	.048	.240
1:16	.011	.004	.535
1:25	.020	.360	No data

Surfaces such as tile, tar and gravel, and corrugated roofs are not fully washed and thus have a greatly reduced washdown effectiveness. Flat roofs, roofs which have a low wetability (smooth aluminum roof panels are an example), or any roof with a slope less than 1:4 are poor for washing decontamination.

Specific problems of roof washdown systems occur with the high contamination concentration at the filter, need for a dry pipe system for freezing climates; requirements for special equipment, water supply, power, special distribution and return piping systems; freezing weather operation; and uncertainty of results.

- b. Roof Blowdown System - A roof air blowdown system, using jets of air to prevent deposition of fallout is feasible, although test results are not available. Advantages of blowdown systems over washing systems are due to avoidance of storage, filtration, and return piping systems, and the application of blowdown to flat roofs. Major disadvantages are ineffectiveness in wet weather and build-up of fallout adjacent the structure in place of the disposal or isolation obtained with the washdown systems.
- c. Disposable Coverings - A disposable cover may be used when fallout occurs over a short time, disposal is only required for the fallout of one detonation and radiation received in the shelter during collection of the fallout on the cover and prior to its removal is acceptable. Canvas or plastic covering which may be rolled onto a mechanically driven or gravity-actuated spool are types of this method of decontamination. Major problems are the safe disposal of the contaminated covering and irregularities and projections above roof surfaces.

#### 8.2.1.3 Discussion of Decontamination

Decontamination requires reliance on a complex, expensive system to achieve an unknown result. Decontamination is essential to some instances, such as on ships, manned exterior facilities which must continue to operate, specific areas within a structure which have an emergency function (such as the upper floors of a structure with micro-wave relay facilities), and for radiological recovery operations. Special structures may have on-site equipment which is suited to decontamination, such as steam generating plant, water treatment plants, and various industrial plants with power, pumping, and water supply readily available. Such structures may



economically employ decontamination as a means of shielding, however for most multi-story structures housing shelters, decontamination is not the most economical or sure means of providing desired shielding results.

## 8.2.2 REDUCTION BY GEOMETRY VARIATION

### 8.2.2.1 Influence of Geometry on Roof Contribution

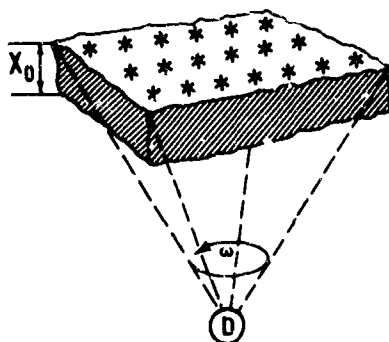
The overhead contribution is determined by the field of view subtended by the contributing area (solid angle fraction) and the mass the radiation must penetrate ( $X_0$ , and  $X_1$  where appropriate). The overhead contribution varies with variation in the solid angle fraction subtended by the contributing area, however with increasing values of  $\omega$ , the change in  $C_0$  becomes smaller. This effect may be noted in Chart 4, Reduction Factors for Combined Shielding Effects. The overhead contribution is nearly proportional to the solid angle fraction when the solid angle fraction is less than 0.1. This solid angle fraction may be visualized as a 20' x 20' core roof 23' over the detector. Variation in  $C_0$  is much less than proportional to  $\omega$  when  $\omega$  is greater than 0.2. The magnitude of variation in overhead contribution with  $\omega$  is dependent on mass for  $\omega$  greater than .2. This is due to the small proportion of the total overhead contribution provided by peripheral areas of heavy roofs, while similar areas of a light roof will provide a higher proportion of the total overhead contribution. Example 8.1 illustrates the effect of variation of solid angle fraction on overhead contribution.

### 8.2.2.2 Geometry Variation Means

Although geometry is not the most critical parameter of overhead contribution, reduction obtained by geometry variation may be significant in lowering the cost of modifications or of incorporating a shelter in new structure design. Principle means of achieving geometry reduction are by:

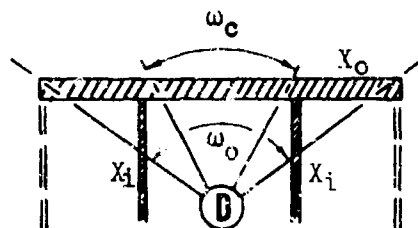
- a. Locating the shelter in a compartmented area, thereby reducing core roof dimensions; and, in effect, reducing peripheral roof contribution by the barrier shielding of interior partitions.
- b. Locating the shelter lower in the structure, increasing the distance from the roof and gaining the barrier effect of the additional intermediate floors.
- c. Locating the shelter area eccentrically within the structure, thereby increasing the average distance to the peripheral roof areas.

# Example 8.1 Parameter Variation Effect on Overhead Contribution



$\omega$	$C_o$							Area* at 10'
	$X_o = 0$	35	65	100	135	165	200	
1.00	1.0	.13	.053	.021	.0083	.0042	.0018	$\infty$
.80	.29	.12	.050	.020	.0081	.0041	.0018	7600sf
.60	.15	.098	.045	.019	.0078	.0040	.0018	2200
.40	.092	.064	.034	.017	.0070	.0037	.0017	580
.20	.042	.029	.018	.0093	.0047	.0027	.0012	180
.10	.019	.013	.0090	.0050	.0026	.0014	.00056	76
.07	.013	.009	.0061	.0036	.0018	.0010	.00050	48
.03	.006	.004	.0028	.0016	.00080	.00045	.00022	20
.01	.0018	.0014	.00095	.00052	.00028	.00016	--	9
.005	.00095	.00068	.00046	.00027	.00014	--	--	6

\* Area of a square subtended by the solid angle on a plane 10ft. over the detector.



$$\omega_o = .6$$

$$X_o = 65\text{psf}$$

$X_i$	$b_1(X_i)$	Net $C_o$					
		$\omega_c =$	.6	.4	.2	.1	.07
0	1.0		.045	.045	.045	.045	.045
20	.50		.045	.040	.032	.027	.022
30	.37		.045	.038	.028	.022	.020
40	.26		.045	.037	.025	.018	.016
50	.19		.045	.036	.023	.016	.013
$\infty$	0		.045	.034	.018	.009	.006

These measures may be taken in selection of an area for modification or in locating a shelter area in proposed new construction. Examples 8.2, 8.3, and 8.4 illustrate situations in which these measures may be used to reduce overhead contribution.

### 8.2.3 REDUCTION BY MASS VARIATION

#### 8.2.3.1 Influence of Mass on Roof Contribution

Variation in overhead contribution due to mass is roughly approximated by case 1, Chart 1 for values of mass greater than 25 psf. As Case 1, Chart 1 is almost linear on the semi-log plot, the correlation indicates that a fractional change in  $C_0$  due to a specific additional mass would be the same through the full range of  $C_0$  values. This effect is illustrated in Example 8.1, where an increase of 30 to 35 psf causes a reduction of about 50% in  $C_0$ .

Varying interior partition mass also has a direct effect on the radiation passing through these partitions.

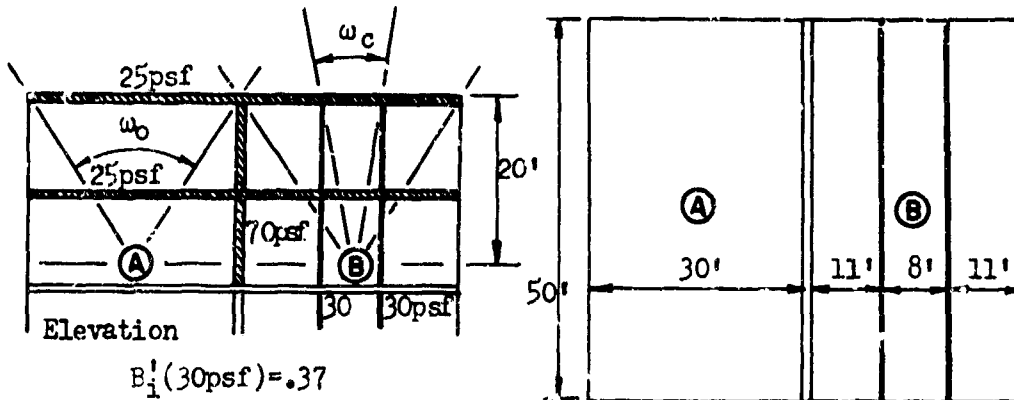
Chart 11 expresses this relationship. Since Chart 11 closely parallels Case 1, Chart 1 it would be expected that the fractional change in  $C_0$  would be similar for mass added to an interior partition and for the same psf incremental increase in overhead mass. Example 8.1 also shows the influence of interior partitions. An important feature however, is that interior partitions only affect peripheral contributions, which are normally very small in relation to the core area contribution.

#### 8.2.3.2 Means of Varying Mass for Overhead Contribution

The choice of location of a shelter area within an existing building can take advantage of existing mass within the building to provide a low overhead contribution. Intervening floors between the shelter and the contaminated roof are the most economical additional mass to reduce the overhead contribution. Increased distance below the roof has the additional geometry effect of reducing the solid angle fraction subtended by the contributing area.

A shelter area in a highly compartmented area of a building makes use of the existing mass of partitions to reduce overhead contribution. The shelter area may itself be compartmented extending through several distinct areas which require separate calculation of protection factor. Partitions which are continuous on adjacent stories and extend to the roof are most effective in providing compartmentalization; however,

Example 8.2 Compartmented Location Effect on Overhead Contribution

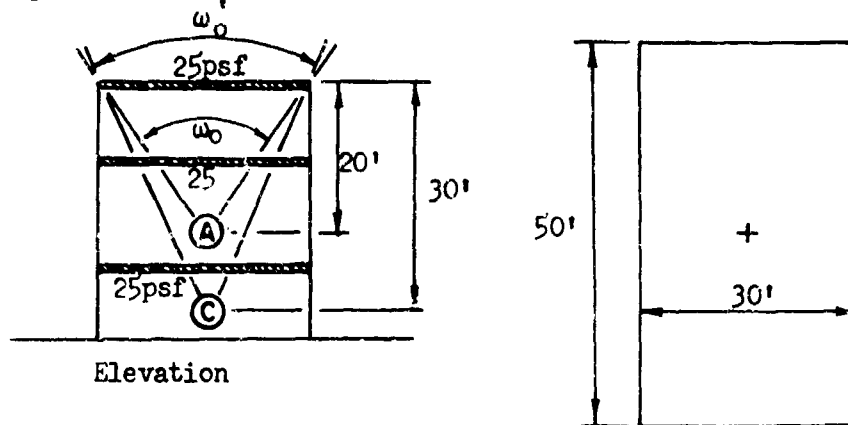


	W	L	e	z	n	$X_o$	$C_o$
$\omega_o$	30	50	.6	20	.80	.32	.038
$\omega_c$	8	50	.16	20	.80	.095	.011

Uncompartmented: Detector A  $C_o = .038$

Compartmented : Detector B  $C_o = .011 + .37 \times .038 = .025$

Example 8.3 Lower Floor Location Effect on Overhead Contribution



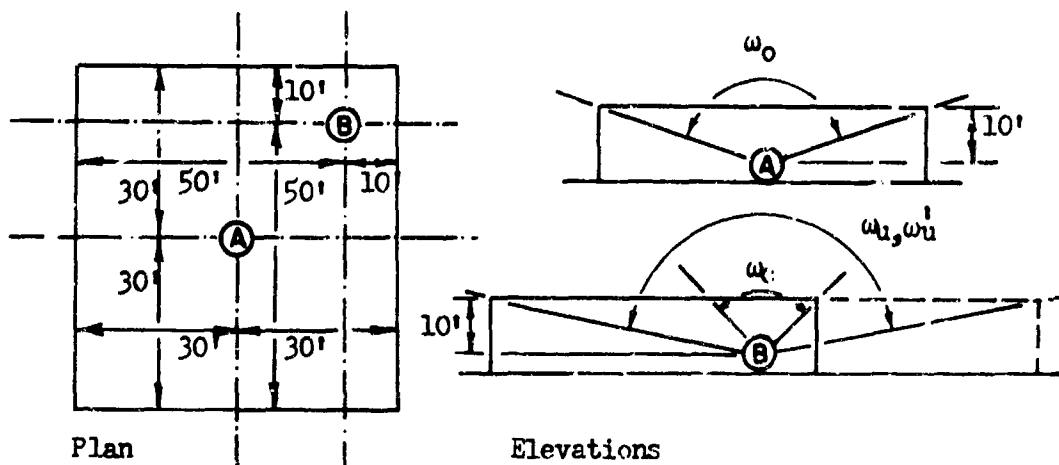
	W	L	e	z	n	$\omega$	$X_o$	$C_o$
$\omega_o$	30	50	.6	30	1.20	.18	.50	.020
$\omega_c$	30	50	.6	30	1.20	.18	.75	.015

Second Floor: Detector A (Example 8.2)  $C_o = .038$

First Floor : Detector C (Geometry effect alone)  $C_o = .020$

First Floor : Detector C (Geometry and added mass)  $C_o = .015$

Example 8.4 Eccentric Location Effect on Overhead Contribution



Central Location : Detector A  $C_o = C_o(\omega_o, X_o)$

Eccentric Location: Detector B  $C_o = \frac{C_o(\omega_c, X_o)}{4} + \frac{C_o(\omega_t, X_o)}{2} + \frac{C_o(\omega_u, X_o)}{4}$

	W	L	e	z	n		$X_o$	$C_o$
$\omega_o$	60	60	1.0	10	.33	.72	25	.15
$\omega_c$	20	20	1.0	10	1.0	.33	25	.060
$\omega_t$	20	100	.20	10	.20	.50	25	.100
$\omega_u$	100	100	1.0	10	.20	.82	25	.16

Central Location : Detector A,  $C_o = .15$

Eccentric Location: Detector B,  $C_o = \frac{.060}{4} + \frac{.100}{2} + \frac{.160}{4} = .105$

discontinuous partitions, located on stories between the shelter area and roof, will reduce overhead contribution even though they are not on the story of the detector. The effect of compartmentalization is reduced with greater total overhead mass thickness, as collimation by this mass causes a greater portion of the roof contribution to come from the roof area directly over the detector. This effect is shown in Example 3.1 as a geometry factor.

Additional mass for the reduction of overhead contribution may be provided in modification or new design by selection of a low-story shelter area and by the selection of the heaviest alternatives of possible floor and roof construction. Provision of heavy interior partitions for reduction of overhead contribution is unwarranted as most of this radiation usually originates from the core area and would not be reduced. This is particularly true in a shelter area with sufficient overhead mass to provide a high protection factor ( $P_F = 100$ ). Example 8.5 shows various means of providing added mass for hasty, temporary, or permanent employment within the structure. Note that floor strength, structure usage, or need for placing mass under emergency conditions can severely restrict the addition of mass to existing floor or roof systems.

#### 8.2.4 DISCUSSION OF MEANS OF REDUCING OVERHEAD CONTRIBUTION

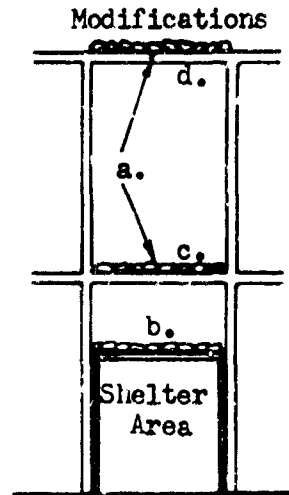
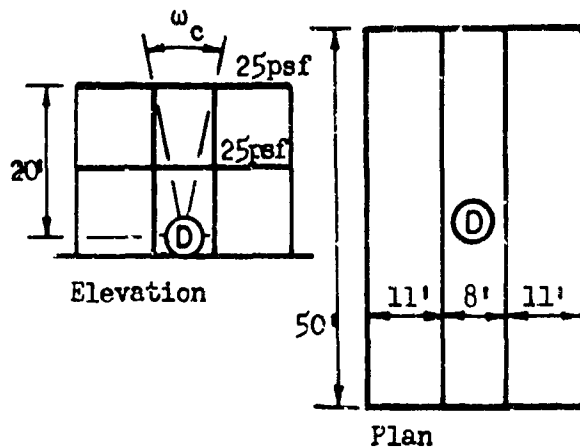
The most economical means of reducing any contribution is by careful selection of the shelter area location within the structure.

Reduction of overhead contribution must be a part of the whole problem of providing a desired degree of protection, and thus must be considered in conjunction with ground contribution. Selection of shelter location for example, directly influences both overhead and ground contribution. Using a lower floor location to achieve greater overhead mass, increases the ground contribution. The single notable exception is adoption of a basement location in which all contributions are reduced. Reduction of height by a story does not increase ground contribution by as large a fraction as that by which the overhead contribution (reference Chart 4) is reduced; however, the actual increase in ground contribution may be larger than the decrease in overhead contribution, due to different magnitude of the two contributions.

Since geometry has little effect on a shelter area which is to have a high protection factor, the desired reduction in contribution will normally be obtained by the addition of mass. While decontamination can greatly reduce overhead contribution, mass in place provides positive measurable protection.

**Example 8.5 Addition of mass to Reduce Overhead Contribution**

GIVEN : Unmodified structure below:



REFERENCE : Example 8.2

Present core roof contribution = .011 =  $C_o$

$w_c = .095$  Present  $X_o = 50\text{psf}$

REQUIREMENT: Reduce core roof contribution to  $C_o)_m = .005$

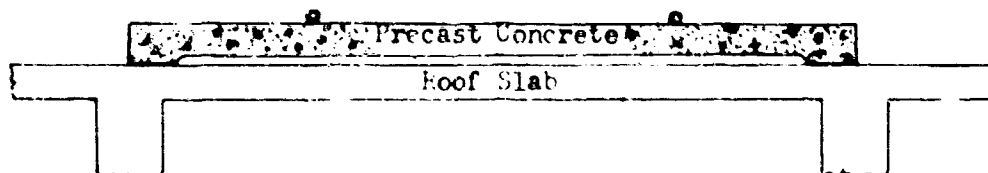
SOLUTION : 1. Determine additional mass thickness required:

$$C_o)_m (w_c = .095, X_o = ?) = .005 \quad X_o = 98\text{psf (Chart 4)}$$

$$\text{Additional mass required} = 98 - 50 = 48\text{psf}$$

2. Location for the additional mass:

- 25psf on both roof and second floor, using bulk material: minimum slab loading, some reduction in peripheral roof contribution.
- 50psf supported immediately over shelter area: maximum bonus reduction in peripheral roof and adjacent story contribution.
- 50psf on second floor: maximum bonus reduction in contribution without a separate supporting frame.
- 50psf on core roof: no bonus reduction in contribution but least disruptive of building use.



In general, it is more economical in the modification of existing structures to reduce the ground contribution and not add mass to reduce overhead contribution. The overhead contribution should be accepted if it is sufficiently small that the desired protection factor may be achieved by reducing ground contribution. In many above ground situations, a lower floor location, which has a higher unmodified protection factor than does a similar location on a higher floor, will be more economical to modify as mass will not have to be added on horizontal planes.

There are no rules which present the most modifying structures. Economy in modification is obtained by skill in fallout analysis and in the chosen design field. Guidelines may be established and illustrations made, however each application will depend upon the ability of the shelter designer.

### 8.3 GROUND CONTRIBUTION

#### 8.3.1 REDUCTION BY GEOMETRY VARIATION

##### 8.3.1.1 Influence of Geometry on Ground Contribution

The ground contribution is determined by the location of the detector with respect to the contaminated field, the size of the contaminated field, and the amount and location of mass through which the radiation must pass. Height, orientation, and amount of mass are parameters of barrier reduction factors. The dimensions of the structure and limits of a limited strip of radiation are essentially geometry factors.

The amount of ground contribution that is received from an infinite field of radiation is dependent on the dimensions and orientation of the contributing exterior surfaces. In vertical section, the principle limits for contributing surfaces are the floors of a building. Thus the radiation received through the exterior wall of the story of the detector is considered separately and is usually of much greater magnitude than the radiation received from the exterior walls of the adjacent stories above and below that of the detector. The location of the floors then, determine the geometry effects on the amount of radiation received.

The effect of geometry on the non-wall scattered components of the radiation received may be visualized from Figure 3.2, the polar plot of non-wall scattered radiation received in an unshielded situation. Note that the bulk of the radiation is received from close to the horizontal. As an illustration of this effect, the ground direct directional response is .42 to a 3' high detector centered on the ground floor of a 48' x 48'

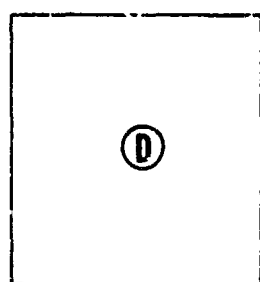


building. If the structure were 24' x 24' instead, or if the detector height were 6' in the original situation,  $G_d$  would be .58, an increase of one-third in  $G_d$ . Chart 6 shows that  $G_d$  changes most rapidly when the non-contributing portion of the field of view (represented by the solid angle fraction) is very large ( $\omega$  greater than .90). Skyshine varies in a similar manner, heavily weighted at the horizontal, however its change with  $\omega$  is not as pronounced as is the change in  $G_d$ .

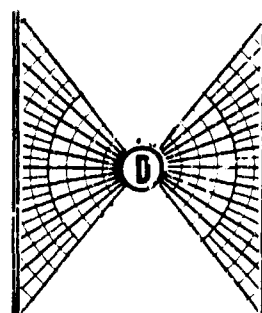
Wall-scattered radiation is essentially proportional to the amount of the field of view subtended by the contributing surface. The detector receives wall-scattered radiation of almost uniform intensity over the entire contributing surface. The shape factor,  $E$ , provides a correction for collimation by the wall, and solid angle fraction weights adjacent wall area more heavily than an area at an acute angle from a normal to the wall from the detector. Example 8.6 examines variation in  $G_d$ ,  $G_a$ , and  $G_g$  due to geometry variation. As illustrated in this example, the principle effect of geometry variation is upon  $G_d$ . Walls of sufficient mass thickness to provide a sheltered area reduce the importance of  $G_d$  in that the fraction of emergent radiation which has not been wall-scattered ( $1-S_w$ ) is small. The most direct geometry factor is detector height above the floor. Variation in this value is critical in comparison to the building dimensions. This can be visualized in the computation of  $n = 2z/L$ , in which slight changes in  $z$  are of much more significance than slight variations in  $L$ .

Another geometry factor in the determination of the ground contribution is the size of the contributing area. Mutual shielding, decontamination, and building setbacks are situations in which the radiation is not received from an infinite field. Pronounced variation in amount of radiation received occurs in such situations. These effects are illustrated in examples in Chapter 6, Detailed Procedure - Complex Applications. Limited contaminated area situations are so varied that only a few generalizations are feasible. Mutual shielding usually causes its greatest reduction in ground contribution on stories above the ground story but below the elevation of adjacent roofs. Decontamination for ground contribution reduction is not generally practical for shelter situations for reasons similar to those discussed for roof decontamination. Other limited contaminated area situations require individual analysis to determine their relative importance. Shielding modifications are generally concerned with such situations when a high protection factor is sought, leaks are checked, or a detailed comprehensive solution is required.

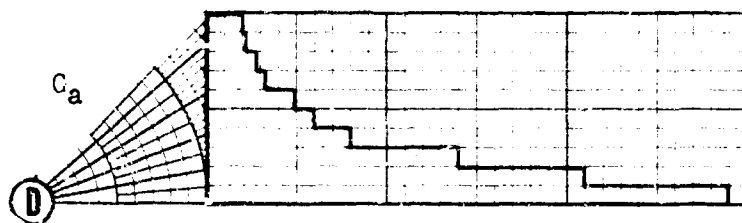
Example 8.6 Influence of Geometry upon Directional Response



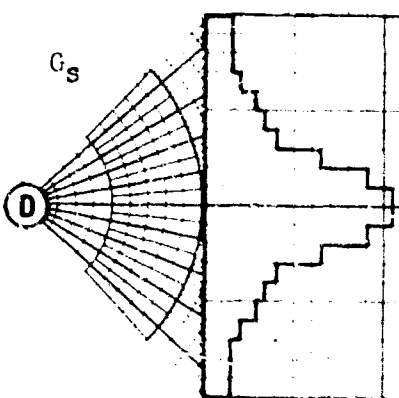
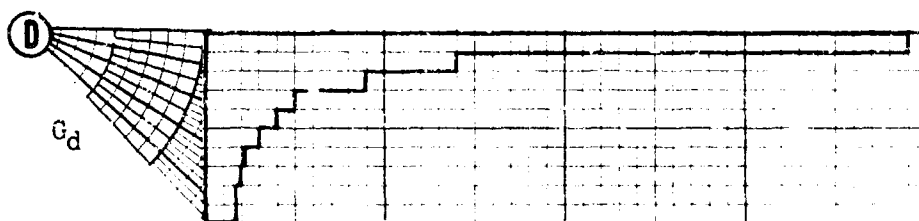
Plan  $e = 1.0$



Elevation



Skyshine scale 10×  
that of  $G_d$



Bar graphs show incremental  
directional response between  
limiting angles.

#### 8.3.1.2 Geometry Variation Means

Selection of the shelter area location within the existing structure is the principle means of securing maximum geometry reduction in a structure. Greatest reduction is generally obtained with a basement shelter location. Location selection should take full advantage of any mutual shielding afforded by nearby or adjacent structures. In some situations, mutual shielding alone may afford such reduction in contribution over that which the same area would receive if there were no shielding, that no modifications are required. Greatest geometry reduction on non-basement stories is obtained with a central location within the building, a detector close to the floor, and maximum height above contaminated plane (note the change of  $G_d$  with height on Chart 6). Shelter usage however, normally dictates the selection of height of the representative detector location, and roof contribution limits maximum height above contaminated plane.

#### 8.3.2 REDUCTION BY MASS VARIATION

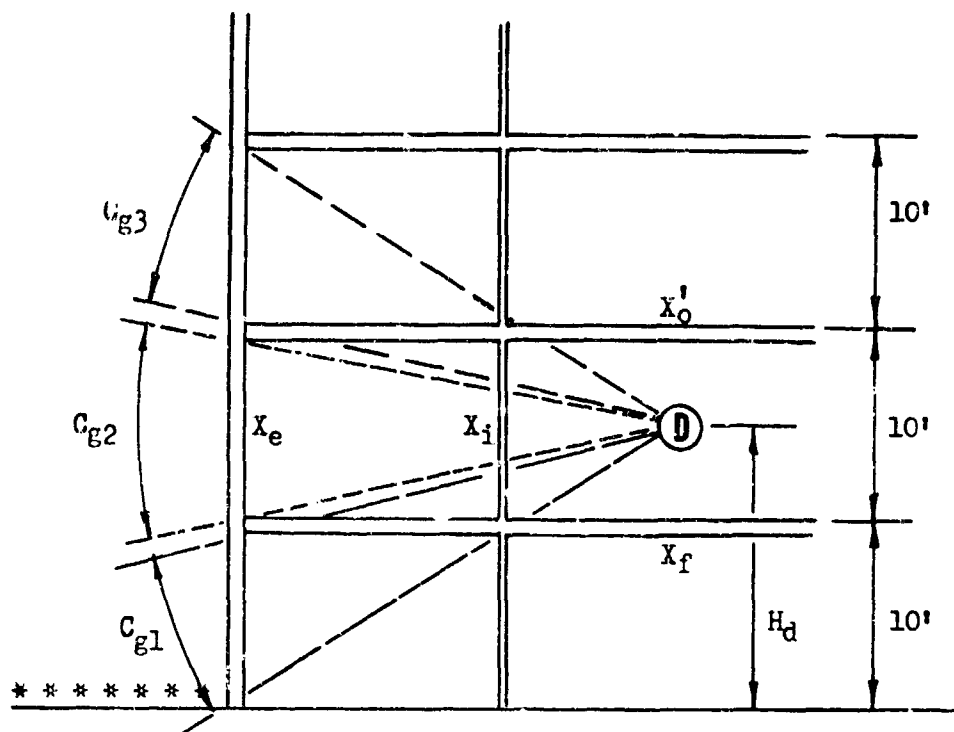
##### 8.3.2.1 Influence of Mass on Ground Contribution

Mass is the most critical factor determining the magnitude of ground contribution. The location of mass determines the parameters of the geometry factors. The orientation of the mass with respect to the detector and to the contaminated area determines its own effectiveness, as may be noted in Charts 1 and 2. Variation in the amount of mass between the detector and the contamination results in exponential variation in the contribution received from that contamination.

A second parameter of the barrier reduction factor, height above contaminated plane, accounts for reduction in radiation due to the mass of air between the contamination and the exterior wall. The barrier reduction factor is affected by this height and the improved effectiveness of the wall barrier due to the collimating of the radiation in passing through this air. The sum of these effects for an exterior wall are given in Chart 2.

The effect of height and variation in the mass of exterior walls, floors, and partitions upon ground contribution are demonstrated in Example 8.7. The effects of mass variation and geometry variation should be compared by reference to both Examples 8.7 and 8.6.

Example 8.7 Influence of Mass on Ground Contribution



$X_e = X_i = X_f = X_o' = 4.0 \text{ psf}$	Change in $C_g$ with Incremental Change in $X$		
	$C_{g1}$	$C_{g2}$	$C_{g3}$
$X_e + 10 \text{ psf}$	-19%	-25%	-23%
$X_i + 10 \text{ psf}$	-18%	-18%	-18%
$X_f + 10 \text{ psf}$	-25%	----	----
$X_o' + 10 \text{ psf}$	----	----	-38%
$X_e + 30 \text{ psf}$	-53%	-57%	-50%
$X_i + 30 \text{ psf}$	-52%	-52%	-52%
$X_f + 30 \text{ psf}$	-58%	----	----
$X_o' + 30 \text{ psf}$	----	----	-73%
$X_e + 60 \text{ psf}$	-76%	-72%	-75%
$X_i + 60 \text{ psf}$	-75%	-75%	-75%
$X_f + 60 \text{ psf}$	-82%	----	----
$X_o' + 60 \text{ psf}$	----	----	-93%
$H_d + 10 \text{ ft.}$	-22%	-21%	-14%
$H_d + 20 \text{ ft.}$	-47%	-36%	-23%

#### 8.3.2.2 Means of Varying Mass

Adding mass to reduce ground contribution is generally the most economical and ready means of improving a shelter. Mass is most effective in stopping radiation when the incidence of the radiation is not normal to its surface. The angle of incidence is greatest for floors and thus mass in floors is more effective than the mass in vertical barriers. Exterior walls at heights greater than 3 feet have their effectiveness increased due to collimation of the radiation in the air; and thus, the same mass per square foot is slightly more effective in an exterior wall than in an interior partition.

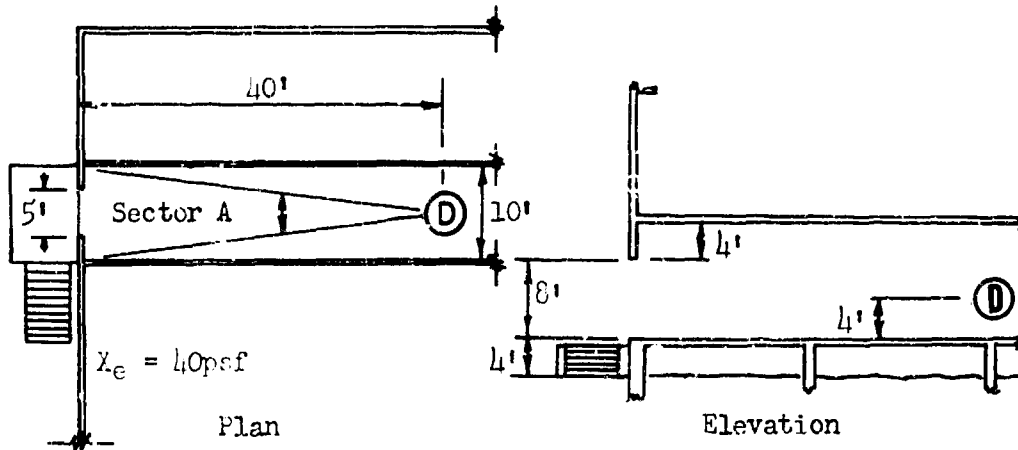
The overwhelming bulk of ground contribution in an exposed story is from the exterior wall on the story of the detector. Mass thickness, in pounds per square foot of surface through which the radiation must pass, is the principle parameter of reduction of that radiation. Maximum reduction is obtained from a given amount of mass by having that mass as close to the detector as possible, as this permits the greatest mass per unit area. As an entire shelter area must usually be protected, the closest practical location for this mass is the limits of the sheltered area itself. Thus, most economical reduction in ground contribution is generally obtained by adding interior partitions at the limits of the shelter area. Exceptions to this usually occur in the correction of leaks, each of which is an individual problem. Example 8.8 illustrates the computation of the amount of mass required to obtain a given reduction in contribution and some of the ways in which this increased mass may be added.

Large reductions due to mass may be achieved in the selection of the shelter location within an existing or proposed structure. Aside from the basement, which is usually the best shelter area, the least ground contribution is found on upper stories. Shelter areas should be located to take full advantage of interior compartmentalization. In new design, the heaviest of alternate choices for wall, partition, and floor construction should be used. High window sills cause all the ground direct radiation to pass through the walls, resulting in a large difference in contribution compared to a low sill situation. In design and construction, low added cost items such as filling masonry blocks with sand or mortar may be employed.

Heavy additional partitions often may be added to existing buildings without structural modifications by placing the partition along column lines. Slab-on-grade situations similarly allow ready modification. The amount of mass and its

Example 8.8 Addition of Mass to Reduce Ground Contribution

GIVEN : Unmodified structure below:



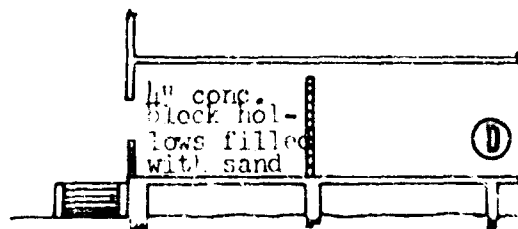
Contribution through the door = .0047  
 Contribution through remainder of Sector A = .00029  
 Total contribution through Sector A,  $C_{gA} = .0050$

REQUIREMENT : Reduce contribution through Sector A to  $C_{gA)m} = .00020$   
 Exit through door not required.

- SOLUTION :
1. Correct leak, the door, by reducing its contribution to that of the adjacent surface. This may be done by providing 40psf up to detector height.
  2. Recompute contribution with leak corrected,  
 $C_{gA} = .00465$
  3. Determine mass thickness to be added as an interior partition:

$$C_{gA} B_i(X_i, 3') = C_{gA)m} \quad B_i(X_i, 3') = .43$$

$$X_i = 35\text{psf}$$



location are shelter analyst problems; economical provision of this mass is dependent on the skill of the shelter designer and is dependent on his ability as an architect or structural designer.

### 3 .4 TYPE MODIFICATIONS

#### 8 .4.1 CATEGORIES

It is convenient to divide types of modifications into three categories: Hasty or Temporary Modifications, permanent Modifications to Existing Buildings, and Shelter Inclusion in New Design. These categories do not characterize the degree of protection afforded by the use of a specific type modification, as an almost unlimited degree of protection could be provided by the use of any of the three types. Further, it would occasionally be desirable to use a combination of modification types to most economically provide suitable shielding.

The categories of modifications can be characterized by:

- a. Use and Nature - Hasty or Temporary Modifications require movement of mass (such as sandbags) to provide shielding, they are apt to by-pass building codes, they may prevent normal use of the area, and they generally require storage areas for materials. Permanent Modifications and New Design provide in-place protection, they must meet building codes (as may be amended for fallout shelters), and they usually allow for a normal use of the area.
- b. Cost - Hasty or Temporary Modifications usually provide the least expensive means of providing a given degree of protection for a given building design. For a permanent shelter it is more economical to include a shelter in new design than it is to modify the same existing structure to provide a similar shelter. Hasty type modifications should be considered for any shelter as in many cases they will be feasible and fully suitable for permanent planning. An example would be the use of sandbags to block basement windows or areaways, to baffle entrances, or to shield ventilating system radiation leaks.

The selection of the type modification to shield a shelter requires economic analysis of possible means of providing a given shelter area a given degree of protection. Such an analysis, and other considerations of degree of risk, possible blast effects, and effect of modifications on structure usage or worth, require judgement based on the general knowledge and professional skill of the architect or structural engineer.

## 8.4.2 HASTY OR TEMPORARY MODIFICATIONS

### 8.4.2.1 Philosophy of Employment

Hasty or temporary modifications are generally the most economical means of modifying an area to provide a given degree of protection. The placement, or planned use of these type modifications are suitable in the following situations:

- a. Permission cannot be obtained to make modifications of a permanent nature.
- b. Such modifications cannot be made within building codes or by altering the use of the affected areas of the building.
- c. A small area must be shielded which cannot be blocked by permanent shielding, such as a door, window, arseway, or corridor.
- d. The structure owner considers that sufficient time will be available after warning to place the shielding.
- e. The modifications are planned or emplaced after the declaration of a national emergency, imminent hostilities, or an outbreak of war.
- f. Military construction and use in a theatre of operations.

Hasty modifications should not be used if it is anticipated that warning of attack and arrival of fallout will not allow sufficient time for placing the shielding, that the anticipated occupants will be incapable of placing the shielding, or that climate will prevent use of the hasty modifications in some seasons.

Hasty or temporary modifications generally involve readily transported heavy material with little structural strength. They are most adaptable to placement on a slab-on-grade, over column lines, or over foundations. Therefore, a large overhead contribution should be avoided to keep cost at a minimum. As the large mass for the planned shielding must be stored and moved into place when required, basement or ground floor shelter locations are desirable.

Possible uses of these type modifications are limited only by the imagination or professional ability of the shelter designer. Properly planned, such modification can provide protection far out of proportion to their cost. This alone should cause their consideration in the planning phase of any shelter.



#### 8.4.2.2 Sample Types

Types of hasty or temporary modifications are too numerous to attempt a complete listing in this handbook. The purpose of the list in Table 8.2 is to illustrate sufficient varieties of such modifications that the designer can visualize appropriate modifications for the specific shelter under study.

Table 8.2 Hasty or Temporary Modifications

<u>TYPE</u>	<u>VARIATIONS</u>	<u>TYPICAL USES</u>
Earth	Other bulk Material	<p>Fill areaways.</p> <p>Bern to cover exposed wali (as for a partially buried basement).</p> <p>Added overhead mass, as by spreading over a floor up to the capacity of the floor.</p> <p>Filler between forms, or to go on a structural support over a shelter area.</p> <p>Filler for hollow blocks.</p>
Sandbags	Sandbags on Pallets	<p>Uses for bulk material given above.</p> <p>Fill window or door openings.</p> <p>Vertical walls, with braces and cross-ties or stacked against a wall.</p> <p>Baffle entranceways or corridors.</p> <p>Shield ducts or small radiation leaks.</p> <p>Shield filter.</p> <p>Shield leaks found during shelter occupancy.</p>
UngROUTED Masonry Block	<p>Palletted brick</p> <p>Tile</p> <p>Block with hollows filled with sand.</p> <p>Cans or drums to be filled with water.</p>	<p>Uses for Sandbags given above.</p> <p>Vertical walls or baffles.</p> <p>Structural support for a separate shelter roof.</p> <p>Compartmentalization within shelter.</p>
Structural Members	Steel sections, Timber	<p>Support modifications described above.</p> <p>Support mass on a separate shelter roof.</p> <p>Form support or hold bulk mass.</p>
Precast concrete	<p>Filled cellular</p> <p>steel flooring,</p> <p>Patented bulk material forms.</p>	<p>Provide prefabricated walls and roof for shelter.</p> <p>Added mass for roof placement.</p> <p>Close doors, windows, areaways, or corridors.</p>

#### 8.4.3 PERMANENT MODIFICATIONS TO EXISTING BUILDINGS

Providing permanent modifications to existing building presents the greatest problems to the designer and is the most expensive of the type modifications. Details of such modifications are not presented as these may be readily visualized by the shelter analyst qualified as a designer due to his architectural or engineering background. Special considerations are presented in Table 8.3 for the shelter planner and type modifications are given in Table 8.4 to assist the planner or designer to visualize the shelter.

Table 8.3 Principle Special Considerations for Permanent Modifications

<u>NATURE</u>	<u>PROBLEM AREAS</u>
Zoning	Building or area capacities. Type of construction permitted. Extent of lot covered.
Building, Safety and Fire Codes	Problem areas of zoning. Construction of partitions. Baffling or blocking doors, windows, and corridors. Required window area and number of entrances. Ventilation requirements. Loading on existing beams, slabs, and columns. Numbers of wash and toilet facilities. Emergency fuel storage. Storage of supplies and equipment.
Labor Unions	Type of construction to be employed. Classification of type of work of varied types of modifications.
Professional Ethics	Addition to, or modification of, original plans of another architect or engineer.
Present building use	Change in characteristics or compartmenting of shelter area. Reduced live load capacities of floors. Interruption of present use for construction. Relocation of utilities.
Reimbursement	Details of Federal, State, or local programs.

Table 8.4 Type Permanent Modifications

(Refer also to Paragraphs 8.2 and 8.3)

<u>RADIATION ENTRY</u>	<u>SAMPLE MODIFICATIONS</u>
Exterior doorway	Interior or exterior baffle or maze of same mass thickness as adjacent wall. Ideal location for hasty sandbag modification. Additional interior partition mass thickness.
Exterior window	Modifications for exterior doorway. Close with block, brick, or concrete.
Exterior wall	Additional interior partition mass thickness. Earth berm to highest practical height, or terraces.
Areaways	Modifications for exterior door and window. Close openings and fill with earth. Concrete slab cover at ground level.
Duct or vent openings	Modifications for exterior door.
Entries into shelter area	Baffle by partitions of mass thickness equal to that of the partition containing the entries.
Core roof	Supported roof over shelter area. Added slab or precast slabs on roof. Decontamination system installation.
Peripheral roof and adjacent stories	Additional interior partition mass. Modifications for core roof.

#### 8.4.4 SHELTER INCLUSION IN NEW DESIGN

The principle special considerations for permanent modification of existing buildings listed in Table 8.3 applies to a slightly lesser extent to new design. New design is less of a problem and more economical than permanent equivalent shielding modification to an existing building for obvious reasons. Major departure from modifications to existing structures occur in the ability of new design to make full planned use of the shielding advantages of location selection, to incorporate required overhead or partition mass in floors or partitions yet to be built, to provide the

necessary structural capacity, and to avoid the problem areas listed for Labor Unions, Professional Ethics, and Present Building Use in Table 8.3.

Desirable location considerations are presented in paragraphs 8.2 and 8.3, as are procedures for determining or satisfying mass requirements. Shelter inclusion in new design requires close integration of shielding analysis skill and professional design ability.

## 8.5 MODIFICATION SELECTION PROCEDURE

### 8.5.1 MODIFICATION SELECTION SEQUENCE

- Step 1 - Select representative detector location in proposed shelter area.
- Step 2 - Compute Protection Factor for selected detector location.
- Step 3 - Compare required and existing Protection Factors.
- Step 4 - Correct leaks, bring to norm of adjacent surfaces.
- Step 5 - Recalculate Protection Factor with leaks corrected.
- Step 6 - Determine those remaining sources of radiation which it is undesirable to correct.
- Step 7 - Correct the remaining sources of radiation to provide the desired Protection Factor.
- Step 8 - Select the actual materials to be used to make the corrections in Step 7.
- Step 9 - Compute the Protection Factor for the Modified Shelter.
- Step 10 - Check the applicability for the rest of the shelter of the Protection Factor found for the detector location.

### 8.5.2 DISCUSSION OF STEPS - (Refer to paragraph 8.5.1.)

Step 1 - A detector location is only chosen to be representative of the shelter area. The Protection Factor will vary slightly (15 to 20%) within a shelter area due to geometry and minor structural variations. Excessive variation may be due to leaks or shielding conditions which only affect a portion of the shelter area. For such situations, the computed Protection Factor must be verified as being representative, or shielding calculations must be made for separate detector locations.

Shelter location should be chosen to make maximum use of available shielding, and to minimize overhead contribution.

Step 2 - Shielding calculation should be made by the Detailed Procedure in the design of permanent modifications or new construction. The Simplified Approximate Procedure may be used for preliminary calculations, or as an alternative to the Detailed Procedure for hasty or temporary modifications.

Step 3 - Comparison of required and existing Protection Factors gives an indication of the magnitude of the task and the nature of the shielding that will be required. Extreme variation will essentially require a structure within a structure (such as the Family Fallout Shelter) with the result that location can be re-chosen without regard to existing shielding.

Step 4 - Leaks are small areas which contribute a disproportionate amount of radiation to the shelter area (doors, skylights, etc.). Leaks are most economically corrected at the opening itself, instead of at the shelter limits, and are often suitable for hasty type modifications. The correction of leaks normally provides the greatest shielding benefit per unit cost. As the leaks are usually at an exterior surface and excess radiation through that surface will normally be corrected by additional mass thickness at the shelter limits, the leaks should only be corrected to provide shielding equivalent to that of the adjacent surfaces. The leak area can then be included with that surface in any further corrections.

Step 5 - In some situations, the correction of leaks may provide sufficient additional shielding to meet the required Protection Factor. In any case the Protection Factor with leaks corrected is required for subsequent modification calculations.

Step 6 - Those sources of radiation should be identified which it is not desirable to correct and whose magnitude permits the required Protection Factor to be obtained even without their modification. Examples of these would be overhead and minor sources of contributions.

Step 7 - The sum of the contributions which are not to be revised is subtracted from the maximum allowable reduction factor to find the desired total contribution of the sources of radiation which are to be modified. This is compared to the as-is contribution of these same sources of radiation.

The required mass thickness of an interior partition may be readily determined by dividing desired reduction factors by as-is reduction factors. The quotient is the required interior partition

barrier reduction factor if there are no interior partitions; otherwise, the present interior partition barrier reduction factor multiplied by the same quotient is the required interior partition barrier reduction factor. In either case, the required mass thickness can be determined directly from Chart 2. A similar procedure may be used for determining additional mass thickness required to reduce contributions from other sectors, the roof, or adjacent stories.

Step 8 - As the required additional mass thickness is determined in Step 7 for each sector, the method of construction, and thereby the actual mass thickness, should be selected. The modified contributions for these sectors should be computed using this actual mass thickness. This procedure permits most economical use of materials.

Step 9 - The computed Protection Factor for the modified shelter should be within 5% of the required Protection Factor, or within other specified limits. Close agreement should be expected as new chart readings of reduction factors are generally not required in this modification procedure (new reduction factors are computed and values of mass are read from the charts).

Step 10 - When the Protection Factor of a shelter is increased by several times, contributions which previously were negligible or approximated may be a significant portion of the total contribution. The analyst must check these contributions, and differences of geometry, or other shielding, which may cause large variation from the modified Protection Factor in other portions of the shelter.

## CHAPTER 9 ENVIRONMENTAL CONSIDERATIONS

### 9.1 GENERAL

Although a potential shelter area may provide excellent shielding from fallout radiation, its worth as a shelter is limited if it is poorly ventilated, deficient in sanitary facilities, or too small for the number of occupants.

### 9.2 AREA AND VOLUME

The term "capacity" refers to the number of persons that can be accommodated in a shelter.

Gross floor area includes such items as columns, fixed equipment, and storage space for shelter supplies. The minimum net floor area allowance per person is recommended to be 10 sq. ft. In addition, at least 65 cubic feet of volume per person should be provided.

Shelter capacity or occupancy time may be limited by the volume of the room and not by its area. This is particularly true if mechanical ventilation is inadequate. In many cases, however, interior stairwells, shafts, and ducts would create enough natural ventilation to extend stay-time markedly.

### 9.3 VENTILATION

The basic requirement for a shelter ventilation system is that it provide a safe and tolerable environment for a specified shelter occupancy time. In areas of very light fallout, occupancy time may be as little as one day. In areas of heavy fallout, it may be as much as 2 weeks or more, but occupants probably could spend some time outside the shelter after the first few days.

The following are important considerations in the ventilation of shelters:

1. Oxygen supply is generally not a critical factor. Carbon dioxide is. The carbon dioxide concentration should not exceed 3 percent by volume, and preferably should be maintained below 2 percent by volume. Three cfm per person of fresh air will maintain acceptable concentrations of both oxygen and carbon dioxide.
2. A combination of high temperature and high humidity in a shelter may be hazardous. An effective temperature of 85° F. should not be exceeded.

3. If recommended sanitation and ventilation standards are followed, odors within a shelter should not be unacceptable under the short-term emergency situation.

Based upon the above factors, the following minimum standards for ventilation may be used as guidance.

1. If no mechanical ventilation is available, a net volume of 500 cu. ft. per person may be used for estimating shelter capacity.
2. If the shelter capacity is based on the minimum space requirements (i.e. 10 sq. ft. and 65 cu. ft. per person), then at least 3 cubic feet of fresh air per minute per person is required.
3. If equipment is available for mechanical ventilation at rates of less than 3 cfm of fresh air per person, with occupancy estimated on the basis of floor area, the net volume of space required per person may be determined from table 9.1.
4. The installation of equipment for the artificial cooling of air for shelter purposes only should be avoided if possible.
5. A heating system generally is not essential. Use of blankets, heavy clothing, etc., for warmth usually will suffice when outside air temperatures are low.

TABLE 9.1 - Relation of space requirements to ventilation

Rate of air change (minutes) <sup>1</sup>	Volume of space required per person Cu.ft.
1,000+	500
600.	450
400.	400
200.	300
100.	200
60	150
35	100
22	65
<sup>1</sup> Computed as the ratio, $\frac{\text{Net volume of space (cu. ft.)}}{\text{Fresh air supply (cfm)}}$	

EXAMPLE for table 9.1, "Relation of Space Requirements to Ventilation"  
Given:

A potential shelter area with clear floor dimensions of 60 by 90 ft., and a ceiling height of 10 ft.



Find:

1. The capacity: based upon adequate ventilation (3 cfm or more of fresh air per person), at least 10 sq. ft. of floor area per person., and at least 65 cu. ft. of space per person.
2. The capacity: based upon no ventilation ( $\frac{1}{2}$  cfm or less of fresh air per person) and 500 cu. ft. of space per person.
3. The capacity: based upon ventilation with 270 cfm of fresh air supplied by a blower.

Solution:

1. Floor area =  $60 \times 90 = 5,400$  sq. ft.  
Volume =  $5,400 \times 10 = 54,000$  cu. ft.

$$\text{Capacity} = \frac{54,000}{10} = 5400 \text{ persons}$$

or

$$\text{Capacity} = \frac{54,000}{65} = 830 \text{ persons}$$

(The smaller capacity, 540 persons, governs.)

2. Volume = 54,000 cu. ft.

$$\text{Capacity} = \frac{54,000}{500} = 108 \text{ persons}$$

3. Volume,  $V = 54,000$  cu. ft.  
Fresh air,  $Q = 270$  cfm

$$\text{Ratio, } \frac{V}{Q} = 200 \text{ min. for air change}$$

From table 3, when  $\frac{V}{Q} = 200$ , the required space per person = 300 cu. ft.

$$\text{Capacity} = \frac{54,000}{300} = 180 \text{ persons}$$

#### 9.4 FILTERS

Weatherproof air intakes should be provided for the ventilation systems of all shelters to keep out rain and fallout particles. For home shelters with hand-operated blowers, a simple hooded intake is considered sufficient. For larger shelters, however, fresh-air intake velocities of mechanical ventilation systems may be high enough to draw fallout particles into the shelters. Therefore, air filters capable of removing at least 90% of 50 micron particles should be

installed. High-efficiency filters that would remove submicron sizes of particles are not required for fallout shelter.

If filters or plenum chambers where radioactive particles can accumulate are in or adjacent to a shelter area, they should be shielded. The following is a guide for sizing the filter shields, which may be walls, or floors above or below the filter:

Intake(cfm)	Mass thickness(psf)
100	40- 60
1,000	80-120
10,000	160-240

#### 9.5 WATER SUPPLY

A supply of potable water is essential. At least  $3\frac{1}{2}$  gallons must be readily available to each occupant. In addition, it is highly desirable to have extra water for hygienic purposes.

Water storage containers should be non-breakable and may be kept within the shelter itself or in nearby readily accessible areas of the building in which the shelter is located.

A reliable well in or adjacent to the shelter area is the best source of supply. However, if it can be assumed that the normal public water supply will be available under war-emergency conditions, consideration may be given to its use. Before relying on this source for drinking water, it should be ascertained that the water would be uncontaminated and that the treatment and pumping plant would be in operation. This requires fallout shelter for the operators and an auxiliary power source if there is likelihood that normal power would be disrupted. If the public water supply is from wells, there would be less danger of contamination by radioactive particles.

Colloidal and soluble radioactive isotopes could be hazardous if sufficient quantities of fallout contaminate a water source. Exposed surface sources such as reservoirs of public water systems are the most vulnerable to this type of contamination. Use of water from these sources may be dangerous for drinking, but not dangerous for such uses as washing or flushing.

To determine the overall water supply available to a shelter area, both outside sources and those within the building should be considered. A most desirable type of outside source would be a large covered water tower or reservoir which is connected to the building by a gravity piping system. To determine actually how much water would be available to a given shelter area, a general analysis must be made of all potential users that would be dependent upon this outside source during an emergency.

In larger buildings, water in hot water tanks, fire reserve tanks, house storage tanks, or in the piping systems may be a good resource. However, water from each source should be checked to see if it is potable. In residences, hot water tanks are excellent sources of potable water; and if ample warning is received, bathtubs and sinks could be filled before the arrival of fallout.

#### 9.6 SANITATION

Because of the confined and crowded living conditions that sheltering might require, sanitation could be a major problem.

Personal cleanliness would have to be encouraged. Metal or plastic hand basins, with buckets for water distribution, would be adequate.

In family shelters, human waste may be disposed of through use of newspapers, plastic bags, or other disposable containers. These would then be deposited in tightly covered containers. A suitable type of chemical toilet may also be used.

In the larger group shelters, regular or austere flush-type toilets, or chemical toilets, should be available on the basis of 1 per 25 occupants. Half of these may be outside the shelter area if readily available in other parts of the building.

Trash and garbage should not be allowed to accumulate. While inside the shelter, it should be kept in tightly covered containers; and it should be deposited outside the shelter area as often as necessary.

#### 9.7 ELECTRIC POWER

In all but family and small group shelters, electric power may be needed to operate motors and to provide light. The greatest load probably would be for the ventilation system. If a special emergency ventilation system is installed, fan motor power requirements may be kept to a minimum. In many cases, it may be more desirable to modify an existing ventilation system. In this case, the minimum power requirement must be determined by the size of the existing fan motors. This may be far more than the basic emergency system requirements.

Other electrical motors that may be required for larger group shelters include those for a water well pump and a sewage ejector pump.

Lighting is not a critical factor in electrical power requirements. A minimum illumination at floor level of only 5 foot-candles should be sufficient for most of the shelter area. Sleeping areas require 2 foot-candles at floor level and administrative and medical areas require 20 foot-candles at desk level.

The best source of emergency electric power is an engine-generator set with a 2 week supply of fuel. The relative merits of gasoline, diesel, and liquefied petroleum gas engines should be carefully considered. Initial cost is important, but so are local code requirements, ease of maintenance, dependability, safety of operation, and storage characteristics of fuels.

Emergency engine-generator sets shall have separate vents and be heat-isolated from the main shelter chamber. Special consideration must be given to the manner of installation of engine-generator sets and fuel tanks to minimize hazards from exhaust gases and fires.

The capacity of emergency engine-generator sets may range from 1 to 10 kilowatts per 100 shelter occupants, depending upon lighting and equipment requirements, and dependability of outside power. Normally, the requirement would be in the lower half of this range.

If the power station has fallout protection, and operational plans provide for the continued operation of the station under fallout conditions, it may be assumed that electric power would be available. Under such circumstances the fallout shelter will not require emergency power.

#### 9.8 ENTRANCES AND EXITS

Entrances, exits, and other openings can markedly affect shelter category and capacity--for example, large garage-type doors in the basement walls of many commercial buildings. Doors of this type, used for belowground shipping service and parking areas, have low mass thicknesses and are in exposed positions. This can result in a low protection factor for basement areas where the factor might otherwise be high.

Baffle walls can be used to shield entryways and other openings. In any given instance the baffle wall should be of a mass thickness that will provide the category of protection desired for the shelter. In most cases this mass thickness should be equivalent to  $X_w$  or  $X_b$ , whichever is appropriate. Exceptions to this will be those cases where the mass thickness of  $X_w$  or  $X_b$  is extremely high (e.g., a granite wall 3 feet thick).

In some cases, stairwells entering shelter areas have open sides and it may be necessary to provide shielding walls to enclose them. In general, the mass thickness of these walls need not be greater than 100 psf.

Accessibility may affect fill-time of a shelter. As an example, the basements of some large buildings may in themselves have high capacity. However, these same areas may be served chiefly by

elevators and may have only one or two narrow stairways for entry. In an emergency, the elevators may not function, and fill-time would be lengthened appreciably.

Local fire codes may be useful in determining accessibility and fill-time. In regard to these two factors, however, it should be kept in mind that a heavy concentration of fallout is not likely to occur immediately following the explosion of a nuclear weapon some distance away.

#### 9.9 HAZARDS

Sometimes areas that offer good protection from radiation are used for storage of dangerous materials or have other dangerous conditions.

Some of the hazards to look for are storage of explosives, or highly combustible materials such as paints, varnishes, and cleaning fluids; or exposed high-voltage equipment.

If the amount of dangerous material in storage is small and readily movable, or the hazard can be isolated, the capacity rating of the shelter should not be affected.

Hazardous utility lines such as steam, gas, etc. should not be located in or near the shelter area unless provision is made to eliminate such hazards before the shelter is occupied.

All shelters shall be constructed to minimize the danger of fire from both external and internal sources.

#### 9.10 OTHER CONSIDERATIONS

Provisions shall be made to insure the shelter interior will remain reasonably dry. When necessary, such items as surface, perimeter and subgrade drainage, damp-proofing and water-proofing shall be accomplished.

Appropriate provisions shall be made for use of ordinary battery-operated radios. This may require installation of suitably designed antenna.

Provision shall be made for the prevention of infestation of the shelter area by insects, rodents, or other pests.

In areas subject to high ground water conditions, provisions shall be made to prevent flotation of the shelter.

General provisions shall be made for the storage of basic shelter supplies by allotting at least one and one-half cubic feet per person. These supplies may include such items as water, sanitary kits, medical kit, radiation meter and food.

CHAPTER 10  
MECHANICAL EQUIPMENT REQUIREMENTS

Frank C. Allen  
Member ASHRAE  
Office of Civil Defense  
Department of Defense

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## SURVIVAL SHELTERS

### MECHANICAL EQUIPMENT REQUIREMENTS

#### INTRODUCTION

In the fluid world of today and tomorrow, adequate and accessible shelter for the people is an essential part of a program to assure our survival as a free nation under any realistic eventuality, including the widespread effects of nuclear warfare. For this purpose the shelter structure is the basic protective element. The structure must provide at least the necessary shielding against the insidious effects of residual nuclear radiations from fallout. This kind of protection would probably be sufficient in most areas and, by taking advantage of the inherent shielding afforded by many existing buildings, can be attained quickly at relatively low cost. However, it is technologically feasible to extend the capabilities of shelters for protection against other weapons effects such as blast overpressures, initial nuclear radiations, atmospheric contaminants and raging or smoldering fires. If we hypothesize that the concepts which determine our defensive posture are not static, changes in emphasis on various aspects of civil defense, including shelter requirements, can be expected. Under continuing research and development programs, ways and means are being explored and evaluated on the basis of cost-effectiveness to satisfy possible long-range conditions as well as to provide better or more economical systems, methods, materials and hardware for meeting requirements in the immediate future.

No structure is a worthy shelter unless it is habitable during the necessary period of occupancy. As one facet of habitability, the physical environment must be maintained within reasonable limits of human tolerance with respect to thermal characteristics and chemical composition of the air. We will consider herein the major parameters and how the physical environment can best be controlled in a shelter which must, by reason of economy, be austere but acceptable to people faced with a situation in which survival may depend upon this protection. It is a thesis of this discussion that a shelter can be planned to facilitate changes which enhance its protective capabilities and yet be constructed and equipped initially to accommodate a lesser objective within a limited budget.

#### GENERAL CONSIDERATIONS

Apart from the effects of enemy attack, there are many interdependent variables which affect the physical environment in which man must live, and the importance of some of these variables is accentuated by the inherent

nature of a shelter and the abnormal conditions under which it may be occupied. Some factors which influence or reflect the thermal and chemical environment in any occupied shelter are as follows:

1. Time of stay in shelter.
2. Number of occupants.
3. Metabolic characteristics of the occupants with respect to sensible and latent heat generated, oxygen consumption, carbon dioxide produced, size, sex, age, and activity.
4. Physiological and psychological reactions of occupants to the immediate situation.
5. Temperature and humidity in shelter space.
6. Clothing (insulating properties, absorptivity).
7. Diet (solid and liquid), including drinking water.
8. Interior heat and moisture sources other than people, such as lights, motors, and cooking appliances (continuous or intermittent).
9. Initial conditions of the shelter environment and its surroundings (temperature distribution, moisture).
10. Rate and method of ventilation with fresh and recirculated air (air conditioning, air motion).
11. Size and configuration of the shelter with relation to interior surface area, volume, geometry, and exposure.
12. Temperature and humidity of fresh air or air supplied to shelter space.
13. Temperature and humidity of air leaving the shelter.
14. Interior surface temperatures and moisture condensation.
15. Weather conditions with respect to variable temperature, humidity, solar radiation, wind, and precipitation.
16. Thermal properties of the shelter and surrounding materials (conductivity, density, specific heat, diffusivity, moisture content).
17. Thickness and thermal properties of cover and shielding materials.

18. Heat flow from adjacent structures or heat sources.

The engineer must first of all distinguish between a structure which is intended for use only as a shelter and one which has alternative uses. The design of mechanical systems and selection of equipment for other than shelter purposes must be governed by building code or local regulations for normal occupancy of such spaces, and the systems must then be adapted as necessary for shelter use.

THE CHEMICAL ENVIRONMENT

Air Vitiation. The normal air components with which we are primarily concerned in shelters are oxygen, carbon dioxide and water vapor. Some degree of control must be provided for these constituents in shelters or any occupied space. We can also consider and provide appropriate measures to protect against the hazards of radioactive fallout particulates and other air-borne toxic, noxious or pathogenic contaminants such as carbon monoxide, hydrocarbon vapors, odorous substances and chemical or biological agents.

An approximate relationship between physical activity, energy expenditure, oxygen consumption, carbon dioxide production and rate of breathing is shown in Table I with reference to the "average" man.

TABLE I  
ENERGY EXPENDITURE, OXYGEN CONSUMPTION,  
CARBON DIOXIDE PRODUCTION AND RATE  
OF BREATHING IN MAN

Physical Activity	Energy Expenditure	Oxygen Consumption	Carbon Dioxide Production	Rate of Breathing
	Btu/Hr	CuFt/Hr	CuFt/Hr	CuFt/Hr
Prone, at rest	300	0.60	0.50	15
Seated, Sedentary	400	0.80	0.67	20
Standing, Strolling	600	1.20	1.00	30
Walking, 3MPH	1000	2.00	1.67	50
Heavy Work	1500	3.00	2.50	75

Oxygen depletion and carbon dioxide buildup are of little concern in properly ventilated shelters, but are important considerations in poorly

ventilated, unventilated or sealed shelters. Oxygen concentrations below 16 per cent and carbon dioxide concentrations above 2 per cent by volume are objectionable, and distress due to these factors would be increased if the abnormal conditions occurred simultaneously or if the time of exposure were prolonged. Oxygen concentrations below 12 per cent and carbon dioxide concentrations above 5 per cent by volume may be acutely dangerous. A limiting concentration of carbon dioxide will develop before oxygen is depleted to a correspondingly restrictive level, that is, unless means are used to absorb carbon dioxide without replacing oxygen. For prolonged occupancy, the intake of fresh air should be sufficient to maintain a carbon dioxide concentration of less than one per cent by volume.

Figure 1 shows the relationship between the concentration of carbon dioxide and oxygen in occupied spaces, the rate of ventilation per person, the volume of space per person and the time after entry. This chart is based upon an oxygen consumption of 0.90 cu. ft./hr/person and a carbon dioxide emission of 0.75 cu. ft./hr/person, which would be representative of people in confined quarters.

The example shown by dotted lines indicates that a carbon dioxide concentration of 3.50 per cent by volume will develop in 10 hours in an unventilated shelter having a net volume of 235 cu. ft./person and that the oxygen content of the air will then be 16.25 per cent by volume.

Control of the chemical environment. Ventilation with pure outside air is the most economical method for maintaining the necessary chemical quality of air in a shelter. The recommended minimum ventilating rate of 3 cfm per person of fresh air will maintain a carbon dioxide concentration of about 0.50 per cent by volume in a shelter occupied by sedentary people. However, it should be noted here that an air replacement rate of 3 cfm per person is not in itself sufficient to limit the resultant effective temperature to 85° F unless the supply temperature is less than about 45° F. This subject will be considered more fully in the discussion of the thermal environment. A capability for maintaining a conservatively low concentration of carbon dioxide and a correspondingly safe concentration of oxygen in a shelter has a number of advantages, including one or more of the following:

1. A longer stay time is gained for continued occupancy after shutdown of a ventilating system because of fire or for repair of disabled equipment.
2. Intermittent operation of a manual ventilating blower may become practicable.
3. Greater physical activity in the shelter becomes permissible.



4. Environmental conditions with respect to temperature, humidity, moisture condensation, air distribution, air motion and odors, as well as oxygen and carbon dioxide may be improved without supplementary apparatus.

Due to the effects of winds and variations in settling velocities, fallout from the high-altitude radioactive cloud formed by a nuclear detonation is distributed downwind in accordance with particle sizes. Particles having mean diameters less than about 50 microns undergo much radioactive decay during their prolonged descent and would probably be deposited beyond the acutely hazardous area. Particles having mean diameters more than 100 microns or terminal velocities higher than 150 ft/min can be largely excluded from a ventilating system by a suitable air intake fixture of reasonable dimensions. It is apparent that filters for the fresh air supply can in some degree contribute to the protection afforded by fallout shelters, particularly if the occupied spaces are shielded by an intervening wall from radioactive particles accumulated by the filters. Although relevant observations indicate that substantial amounts of radioactive fallout particulates are not likely to enter a shelter via the ventilating system, more conclusive information is being pursued to evaluate the significance of this mode of contamination and to compare the cost-effectiveness of alternative procedures for improving shelters. In general, any air filtering requirement in fallout shelters is for apparatus to remove particles larger than 10 microns with a graded moderate to high efficiency rather than to remove sub-micron particles with very high efficiency. Air filters increase the effort needed to operate a blower with a manual drive and may be omitted in small fallout shelters.

For a situation wherein the outside air is contaminated by pathogenic organisms or toxic gases, either suitable gas-particulate filters may be provided or the ventilating system should be shut down temporarily. Due to the presence of heated air and carbon monoxide, shutdown of the ventilating system may also be necessary during the course of a fire adjacent to a fresh air intake opening. A closed environmental or life support system is indicated for prolonged periods without ventilation. When a ventilating system is shut down, pressurization of the space is lost, and the shelter must be well sealed to prevent the infiltration of contaminated outside air.

Intermittent Blower Operation. To maintain the chemical quality of air in a shelter with minimum effort, a manually driven blower having more than minimum capacity can be operated intermittently. Answers to some questions about operating schedules can be readily obtained from Figure 2. On this chart the minimum ventilating rate in cfm per person of fresh air is equated to the minimum blower operating time expressed as a percentage of an ON-OFF cycle time, and the net free volume of shelter space in cubic feet per person is equated to the maximum blower shutdown time expressed as a percentage of the same ON-OFF cycle time. The chart is based on a carbon dioxide production rate of 0.80 cubic feet per hour per person, and a carbon dioxide concentration which varies during the cycle between the limits of 0.67 and 2.00 per cent by volume.

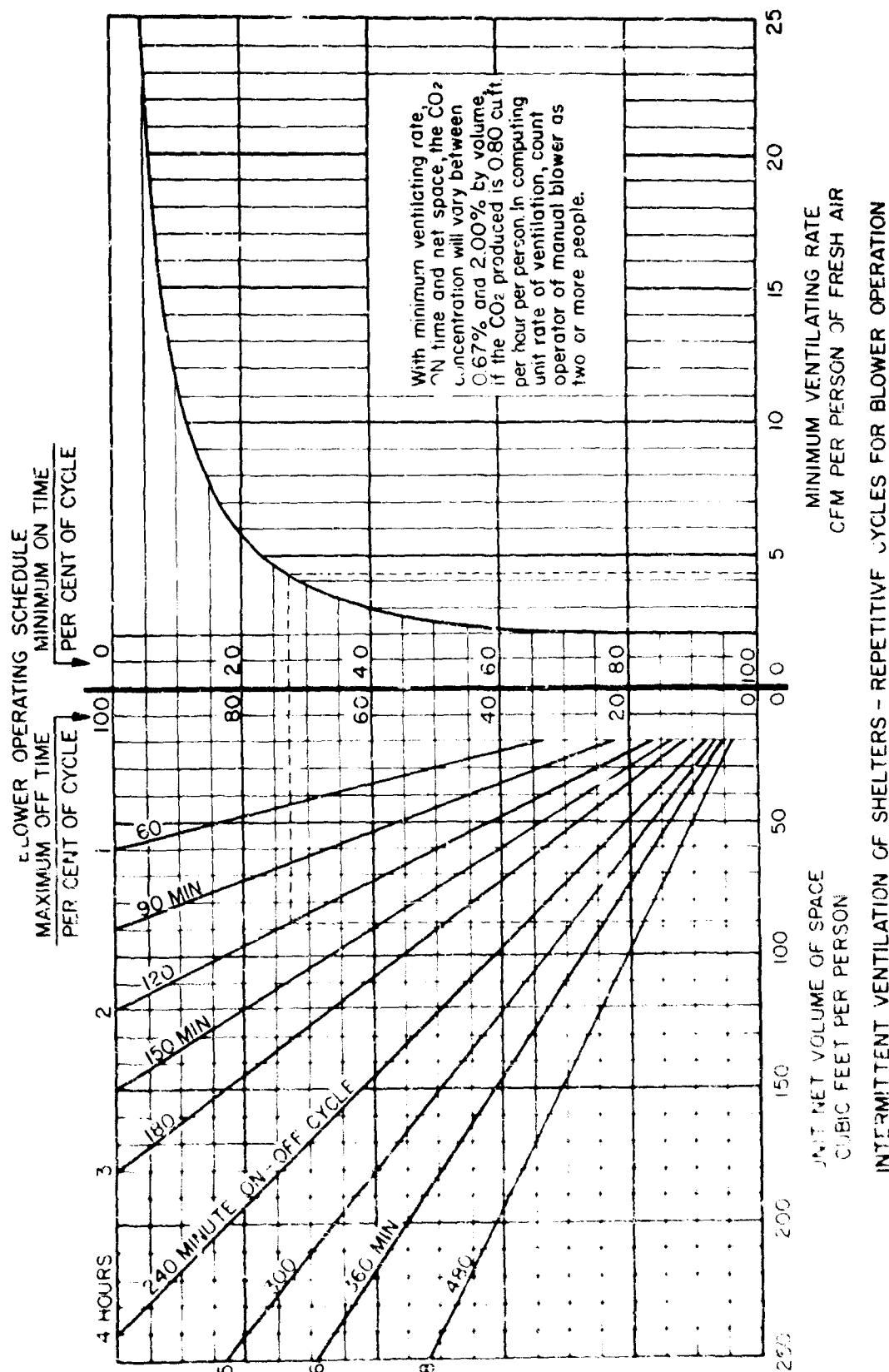


FIG. 2

INTERMITTENT VENTILATION OF SHELTERS - REPETITIVE CYCLES FOR BLOWER OPERATION

In the example shown by dashed lines, it is known that the volume of free space in a shelter is 88 cubic feet per person. The blower may then be operated on a 2-hour ON-OFF cycle if the installed blower capacity is 4.3 cfm per person or more, with a minimum ON time of 27 per cent or 32 minutes and a maximum OFF time of 73 per cent or 88 minutes. If the ventilating rate is greater than 4.3 cfm per person or if the ON time is more than 27 per cent, the maximum carbon dioxide concentration will be correspondingly less than 2 per cent by volume.

#### THE THERMAL ENVIRONMENT

Heat and Moisture Sources. Some of the internal heat and moisture sources in shelters are the people, lights, cooking appliances, radios, motor-driven equipment and auxiliary power apparatus. Heat resulting from human metabolism must be almost continuously removed from the body. While the body can store heat temporarily, this produces a rise in body and skin temperatures and results in progressively increasing heat stress. Heat storage is necessary in a warm humid environment when a state of equilibrium between the energy expended and the total heat loss cannot be attained at a normal body temperature. Activities to be expected in shelters would probably lead to per capita energy expenditures within the range of 300 to 600 Btu per hour with a mean of about 400 Btu per hour. However, the daily average energy expenditure would probably be less than 400 Btu per hour per person because of the reduced metabolic rates for sleeping people and small children. An effective temperature of 85° F is about the maximum condition under which the energy expended by mildly-active persons can be removed from the body without heat storage, and is the recommended maximum inside design condition for shelters. With still or slowly moving air, several combinations of temperatures and humidity for which the effective temperature is 85° F are shown in Table II. Moisture can be expected to condense on interior surfaces having a temperature below the indicated dewpoint temperature of the air.

TABLE II  
TYPICAL COMBINATIONS OF AIR CONDITIONS  
FOR WHICH  
THE EFFECTIVE TEMPERATURE IS 85°F

Effective Temperature	Dry-Bulb Temperature	Wet-Bulb Temperature	Dew-Point Temperature	Relative Humidity
° F	° F	° F	° F	%
85	85	85	85	100
85	90	82	80	72
85	95	79	73	50
85	100	76	66	34



The partition of total heat loss from the human body into sensible heat and latent heat is largely dependent upon the dry-bulb temperature of the environment. For a nominal heat loss of 400 Btu per hour per person, Table III shows a probable relationship between the dry-bulb temperature, total heat loss, sensible heat, latent heat, and amount of water evaporated. The tabulated values are derived from several sources and are suggested as representative for a sedentary or mildly-active adult person wearing optimum clothing in thermal equilibrium with the rather humid environment of a ventilated shelter. At temperatures above 85°F, the quantities for moisture evaporated may not be attainable if the relative humidity is high, and the resultant deficiency in latent heat loss would then cause the body temperature to rise. The validity of the sensible heat losses at dry-bulb temperatures below 70°F is contingent upon the addition of appropriate layers of clothing to maintain normal skin temperatures. A person wearing inadequate clothing would react to a chilling effect as the environmental temperature falls below 70°F, and the attendant values of total and sensible heat losses would then be considerably higher than those shown in Table III. The quantities of water evaporated are related to the requirement for drinking water in shelters at various environmental temperatures.

TABLE III  
RELATIONSHIP BETWEEN AIR TEMPERATURE  
HEAT LOSSES AND MOISTURE EVAPORATED  
FOR AVERAGE SEDENTARY MAN  
WITH OPTIMUM CLOTHING

Dry-Bulb Temperature	Total Heat Loss *	Sensible Heat Loss	Latent Heat Loss	Moisture Evaporated
°F	Btu/hr	Btu/hr	Btu/hr	Lb/Hr
40	400	350	50	0.048
45	400	350	50	0.048
50	400	350	50	0.048
55	400	350	50	0.048
60	400	345	55	0.053
65	400	335	65	0.062
70	400	320	80	0.077
75	400	300	100	0.096
80	400	270	130	0.125
85	400	220	180	0.173
90	400	120	280	0.269
95	400	20	380	0.365
100	400	-80	480	0.461
105	400	-180	580	0.557
110	400	-280	680	0.653

\*400 Btu/hr is equivalent to 117 watts

Under emergency conditions, illumination can be reduced to a low level, if necessary, with a resultant heating effect of 0.50 to 1.00 watts per square foot of floor area. Heat and moisture from other sources can be removed directly without affecting the living and bunking areas by a simple exhaust system or by grouping the utility areas to best advantage.

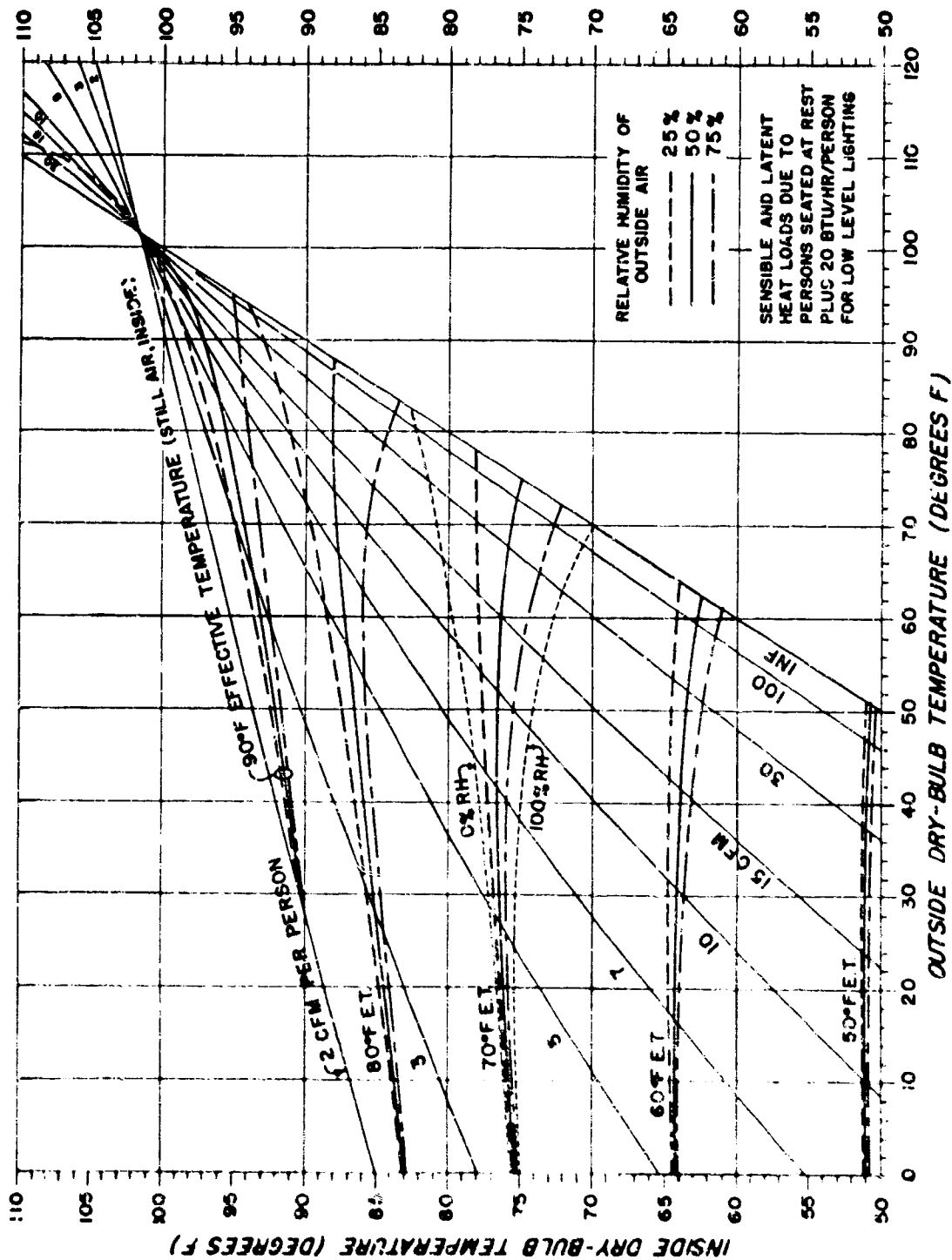
There are three more-or-less distinct procedures which may be used to control the thermal environment in a shelter during warm or humid weather: (1) cooling by forced or natural ventilation with outside air, (2) cooling by the effects of heat conduction into the surrounding earth and (3) mechanical cooling and dehumidifying with refrigeration or well water. Various combinations may be utilized. In general, only method 3 provides positive and reliable control of temperature, humidity and moisture condensation.

Cooling by Ventilation. The curves in Figure 3, can be used to estimate the ventilating air requirements for control of environmental conditions in occupied spaces. On this chart various per capita rates of ventilation are plotted as a function of outside and inside dry-bulb temperatures and upon this background are superimposed the 50, 60, 70, 80 and 90° F still-air inside effective temperature curves for outside air relative humidities of 25, 50 and 75 per cent. The 70° F inside effective temperature curves for outside relative humidities of 0 and 100 per cent are also shown. The heat and moisture loads upon which this chart is based consist of the sensible and latent heat emitted by a man seated at rest plus 20 Btu/hr/person for low level lighting, that is, about 6 watts per person. Other internal heat loads and the transient cooling effect of earth conduction are not considered.

The chart may be used to estimate the supply air quantity, temperature and relative humidity necessary to maintain a given effective temperature in a shelter. For instance, an effective temperature of 80° F can be maintained in a shelter with 15 cfm of air per person distributed at a dry-bulb temperature of 78° F and 50 per cent relative humidity. The dry-bulb temperature in the shelter would be 88° F.

Convenient data are plotted in Figure 4 to show the quantities of outside air required at various dry-bulb temperatures and relative humidities to maintain an inside effective temperature of 85° F. Similar data are plotted in Figure 5 to show the quantities of outside air required at various dry-bulb temperatures and relative humidities to maintain inside effective temperatures of 80° F and 90° F. The curves graphically illustrate the limitations for adequate cooling by ventilation during hot weather, particularly when the outside air is humid.

The curves in Figure 4 show that 3 cfm per person of fresh air, which was sufficient for controlling the chemical environment could not without supplementary cooling maintain an inside effective temperature of 85° F or less, when the outside air temperature is higher than about 45° F. The curves in Figure 5 show that, with 3 cfm per person of fresh air, inside effective temperatures of 80° F or 90° F can be maintained only when the outside air temperature is less than about 30° F or 60° F



VENTILATING AIR REQUIREMENTS FOR CONTROL OF ENVIRONMENTAL CONDITIONS IN OCCUPIED SPACES

FIG. 3

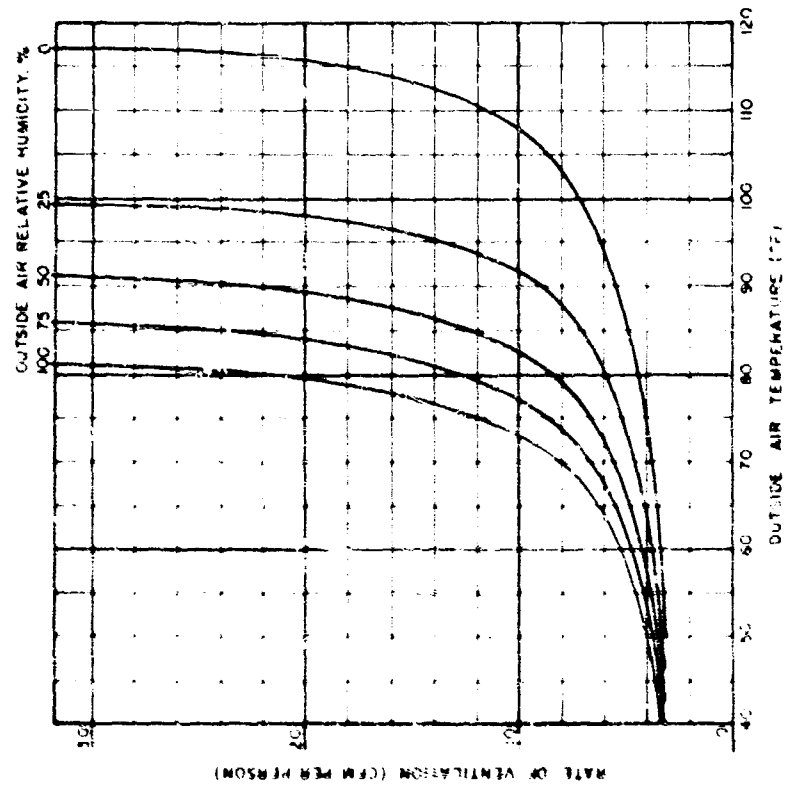
respectively. Thus it is apparent that 3 cfm per person of outside air is not sufficient by itself to maintain an effective temperature of even 90°F during a significant proportion of the year. It can be said explicitly that an air replacement rate as low as 3 cfm per person is adequate only when (1) the outside air temperature is low, (2) the cooling effect due to earth conduction is high by virtue of a combination of a large interior surface area per person, a low initial earth temperature and favorable soil conditions or (3) supplementary cooling or dehumidifying apparatus is provided using mechanical refrigeration or well-water heat-transfer coils.

Some representative values from the curves of Figure 4 and Figure 5 are shown for comparison in Table IV. An inspection of the tabulated values leads to the conclusion that the recommended maximum effective temperature of 85° F or less can be maintained in a shelter with a ventilating rate of about 15 cfm per person in most localities, except during extreme conditions of temperature and humidity. With lower rates of ventilation, supplementary cooling or dehumidification would often be required. Under favorable conditions the necessary supplementary cooling can be provided by earth conduction effects. During cold weather the intake of fresh air should be reduced as necessary to avoid overcooling, preferably by recirculating part of the air rather than by reducing the total rate of ventilation.

TABLE IV  
QUANTITY OF AIR REQUIRED FOR  
COOLING A SHELTER BY VENTILATION  
(CFM PER PERSON)

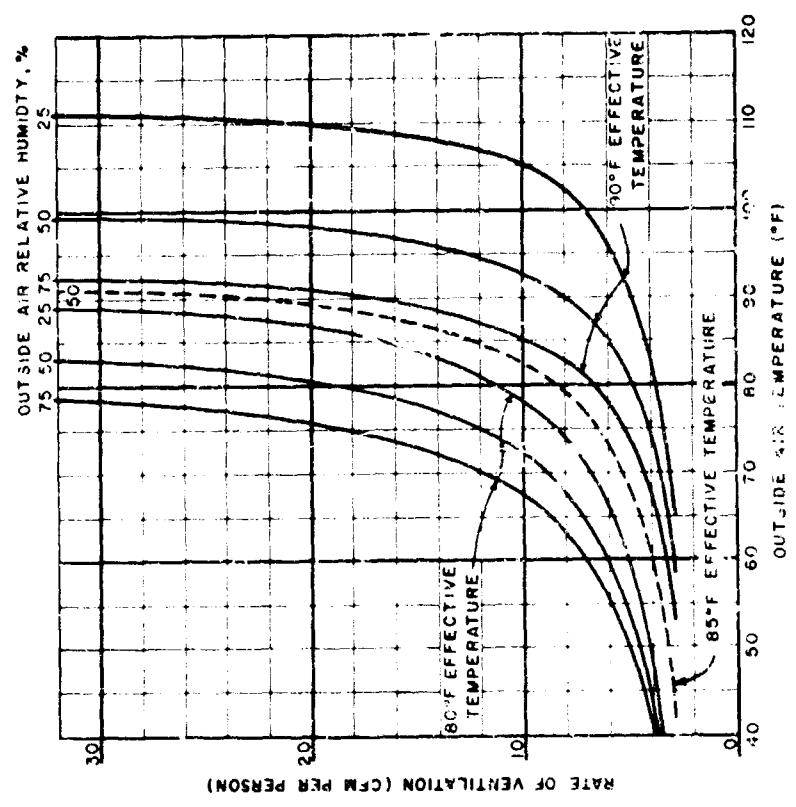
Inside Effective Temperature (°F)	Supply Air Dry-Bulb Temperature (°F)	Relative Humidity of Supply Air (Per Cent)		
		25	50	75
80	75	8.4	12.0	18.4
	80	11.2	18.8	*
	85	16.6	*	*
	90	*	*	*
	95	*	*	*
85	75	5.2	6.7	8.7
	80	5.9	8.5	12.7
	85	7.0	12.4	24.0
	90	9.0	22.5	*
	95	13.6	*	*
90	75	3.4	4.1	5.2
	80	3.8	4.9	6.3
	85	4.3	6.0	9.9
	90	4.9	8.0	17.0
	95	5.8	12.7	*

\*Values greater than 30 cfm per person



COOLING BY VENTILATION WITH OUTSIDE AIR  
 QUANTITIES OF AIR REQUIRED TO MAINTAIN AN EFFECTIVE  
 TEMPERATURE OF 65°F IN A SHELTER

FIG. 4



COOLING BY VENTILATION WITH OUTSIDE AIR  
 QUANTITIES OF AIR REQUIRED TO MAINTAIN AN EFFECTIVE  
 TEMPERATURE OF 80°F OR 90°F IN A SHELTER

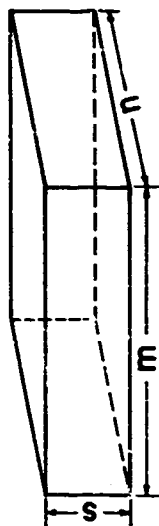
FIG. 5

**Earth Conduction Effects.** The relatively cool soil or rock surrounding an underground shelter would absorb heat at a rate which is high at first, but the rate would diminish with time as a temperature gradient is established in the adjacent material. The heat absorption is accompanied by a rise in temperature of the interior surfaces. This transient effect provides appreciable supplementary cooling which retards the rate at which the shelter temperature rises. An analytical study has been made of the earth conduction effect alone for three sizes of shelters and five types of adjacent soils, using a computational method for heat transfer in deep underground chambers included in the Corps of Engineers Manual, "Heating and Air Conditioning of Underground Installations." This method considers two cases: (1) a constant heat input and (2) a constant maintained temperature in the chamber. Data on the shelters and soils studied are tabulated in Figure 6. Most fill materials would have significant thermal properties within the range represented by Soils M2 and M4, that is, thermal diffusivities between 0.020 and 0.040 Sq Ft/Hr, and thermal conductivities between 0.50 and 1.40 Btu/(Hr x Ft x °F). The heat load in all three shelters is assumed to be 400 Btu/Hr per man plus 2 Btu/Hr per square foot of floor area for low level lighting. The results of the study are plotted as curves on Figures 7, 8, 9 and 10.

Figure 7 shows the effects of unit surface area on the time required to reach an effective temperature of 85° F in 2, 7, 14 and 30 days for two soil types, M2 and M4. For example: In a medium shelter with soil type M2, an initial earth temperature of 64.6° F, and an inside surface area of 87 sq.ft/man, an effective temperature of 85° F would be reached in 7 days. The unit heat load is 5.2 Btu/hr per square foot of surface. With the same soil type and initial earth temperature, and an inside surface area of 122 sq.ft/man, an effective temperature of 85° F would be reached in 14 days. The unit heat load would be 3.9 Btu/Hr per square foot of surface.

Figure 8 shows the effects of various soils on the unit area of surface required to avoid an effective temperature higher than 85° F in 14 days in a medium shelter. For example: With soils M2, M3 and M4, and an initial earth temperature of 61.4° F, the required unit surface areas to just reach an effective temperature of 85° F in 14 days would be 103, 65 and 47 sq. ft/man respectively. The corresponding unit heat loads would be 4.5, 6.8 and 9.2 Btu/Hr per square foot of surface.

Figures 9 and 10 illustrate the difference in earth conduction effects between the small and large shelters. For example: With soil M3 and an initial earth temperature of 64.5° F, an inside effective temperature of 85° F would be reached in 14 days if the inside unit surface area is 66 and 86 sq.ft/man respectively in the small and large shelters. The corresponding values for unit heat load are 6.5 and 5.5 Btu/Hr per square foot of surface.



KEY DIAGRAM

DATA ON SHELTER CONFIGURATIONS

SHELTER SIZE	LENGTH m (FT.)	WIDTH n (FT.)	HEIGHT s (FT.)	FLOOR AREA	VOLUME (C.U.FT.)	SURFACE AREA
SMALL	15	15	10	225	2250	1050
MEDIUM	30	30	10	900	9000	3000
LARGE	60	60	10	3600	36000	9600

THERMAL PROPERTIES OF SURROUNDING EARTH

SOIL	K	$h^2 = \frac{K}{\rho c}$	p	c	DESCRIPTORS
M1	0.20	0.0125	80	0.20	Light Soil, Dry
M2	0.50	0.020	89	0.28	Light Soil, Damp
			125	0.20	Heavy Soil, Dry
M3	0.90	0.030	130	0.23	Heavy Soil, Damp
			143	0.21	Concrete, Damp
M4	1.40	0.040	117	0.30	Wet Soil
			175	0.20	Average Rock
M5	2.00	0.050	200	0.20	Dense Rock

Total Heat Load = 400 Btu/Hr/Man + 2 Btu/Hr/Sq.Ft. of Floor Area

Surface Film Coefficient (Convection) = 1.50 Btu/Hr/Sq.Ft./°F

BASIC DATA FOR ANALYSIS OF SEVERAL CLOSED DEEP

UNDERGROUND SHELTERS TO AVOID EFFECTIVE TEMPERATURES  
IN EXCESS OF 85 °F DURING PROLONGED OCCUPANCY

FIG. 6

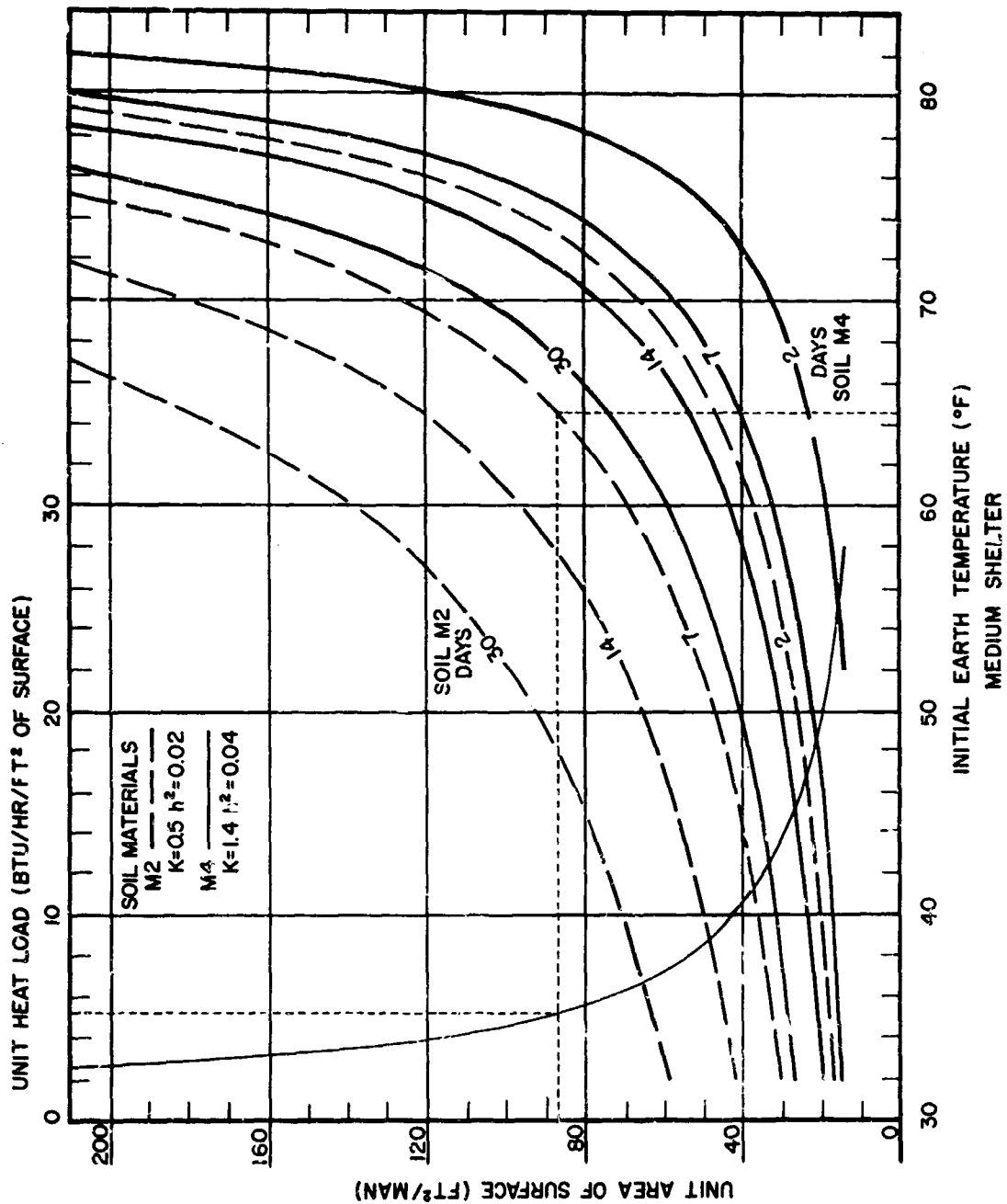
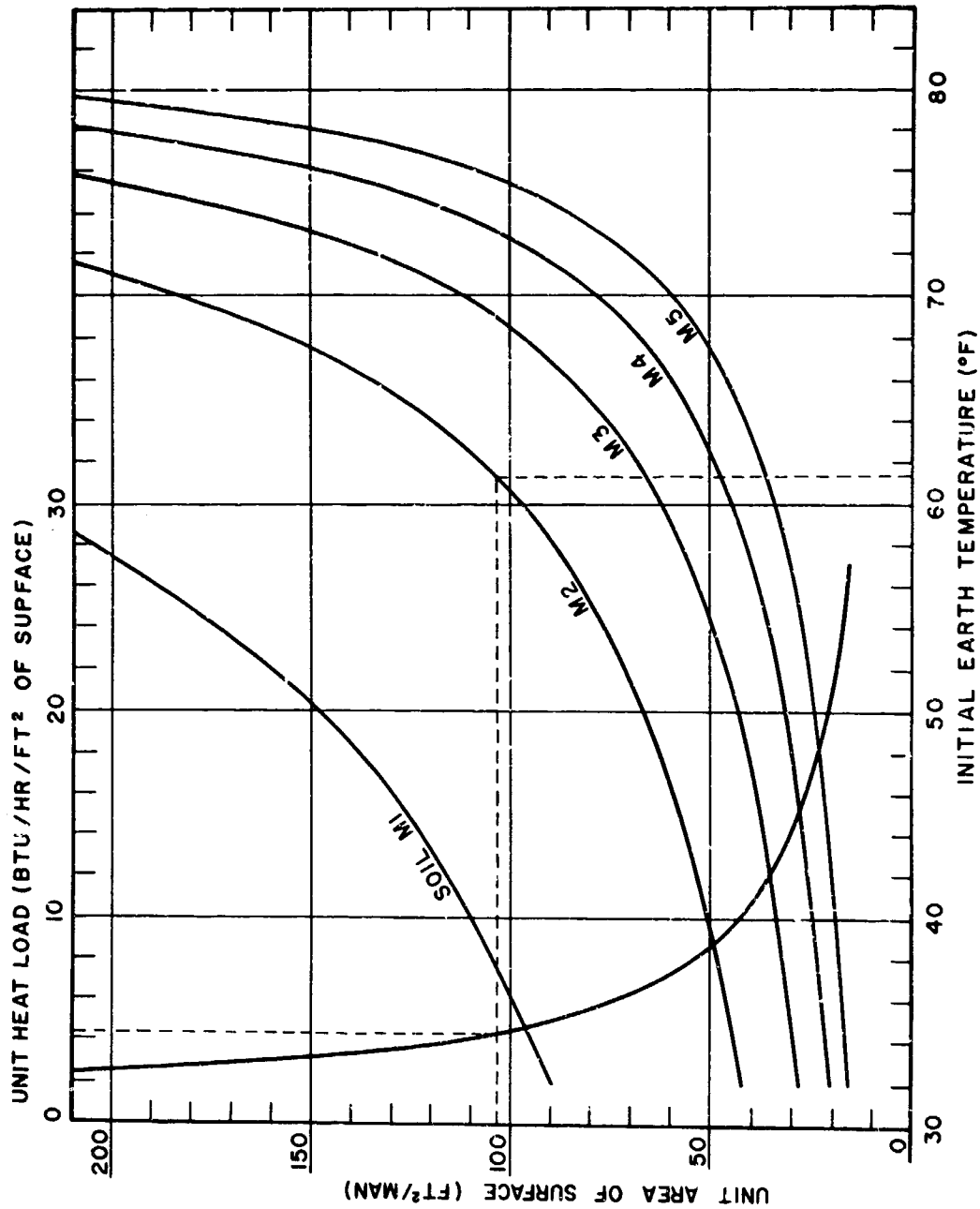


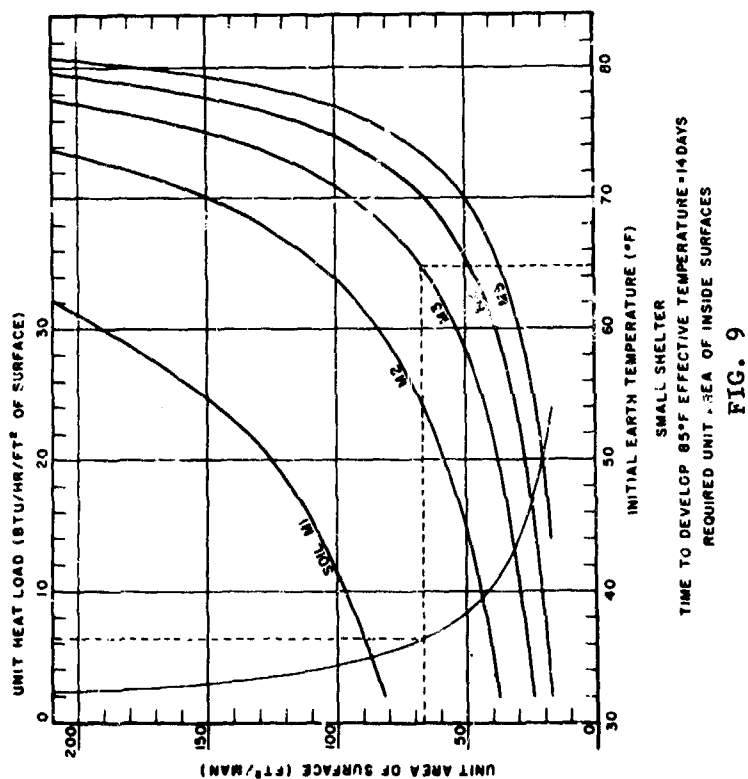
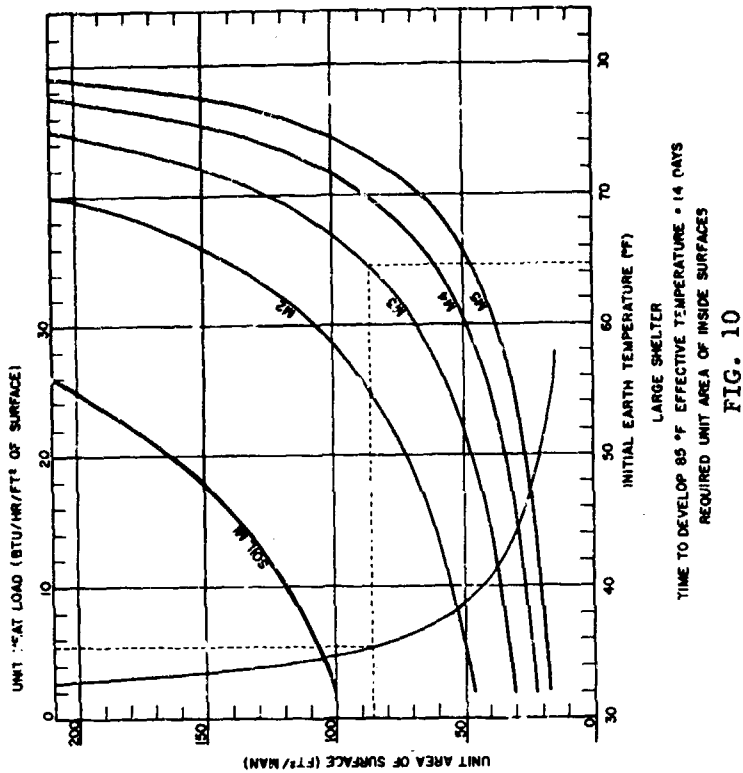
FIG. 7





TIME TO DEVELOP 85°F EFFECTIVE TEMPERATURE = 14 DAYS  
MEDIUM SHELTER  
REQUIRED UNIT AREA OF INSIDE SURFACES

FIG. 8



It is apparent from a study of the curves in Figures 7, 8, 9 and 10 that the thermal properties of the soil, the initial earth temperature and the stay time in a shelter have an important effect upon the interior unit surface area required for the adequate removal of heat from underground shelters by earth conduction. The conductive cooling effect in shelter roofs having shallow cover would be reduced in warm weather, and to a greater degree if the upper surface is exposed to solar radiation.

Since the interior surface area per person tends to decrease as the size of a shelter increases, the contribution made by earth conduction effects to cooling requirements becomes proportionately less in large shelters. However, earth conduction effects may be sufficient in conjunction with adequate replacement of the air to maintain a habitable physical environment in an underground survival shelter. Therefore, under favorable conditions the necessity for providing a more expensive system can be avoided.

Mechanical Cooling. An environmental control system which uses either mechanical refrigeration or well water for cooling and dehumidifying has a number of advantages including the following.

1. Temperature and humidity can be controlled within any desired limits.
2. The system can function effectively during hot, humid weather.
3. Moisture condensation can be eliminated.
4. The amount of fresh air required and the size of the ventilating openings can be minimized.

A well and pump for potable and cooling water is most desirable in a shelter for other purposes as well as domestic uses. Air cooling and dehumidifying with water coils can be accomplished at low cost with well water. Well water can also be used to cool refrigerant condensers and to cool emergency engine generators either directly or with an auxiliary heat exchanger. Air cooling with mechanical refrigeration may be necessary in some climatic locations where cooling is essential and lower cost methods are not feasible.

Adjacent Fires. If the air intake fixture for a shelter ventilating system is close to a fire or smoldering materials, temporary shutdown of the system might be necessary to prevent the ingress of carbon monoxide and heated air. Also, heat from a fire or smoldering rubble on the ground above a shelter might penetrate the cover materials and overheat the shelter space. Figure 11 shows the ratio of the temperature rise of the inside surface to the initial temperature difference as a function of time for cover materials having thermal diffusivities of 0.02, 0.03 and 0.04 sq. ft/hr. For example: if the fire temperature is 1500° F, the initial temperature of the cover material is 60°, and the thermal diffusivity is 0.03 sq. ft/hr, the inside surface temperature rises of a 2-foot thick cover after 8 and 16 hours are

0090 :: 1440 = 13° F and 0.083 x 1440 = 120° F respectively, and the inside surface temperatures are 73° F and 180° F respectively.

Heating. In cold climates, some capability for heating is desirable to temper ventilating air or to avoid low or freezing temperatures when the shelter is not in use. Environmental temperatures of 50° F or even lower can be endured if winter clothing is available, the diet is adequate and the people are in good health. Heat produced by the occupants will be effective in progressively warming the space, and this effect may be sufficient, particularly in underground shelters. Since the requirement for heat is relatively small, electric resistance heaters are convenient and economical for this purpose. If an auxiliary power supply having a liquid-cooled engine is provided, waste heat can readily be used for both space heating and domestic hot water. Fuel burning appliances which take air for combustion from the occupied spaces and are not directly vented to the atmosphere may be hazardous and should be avoided.

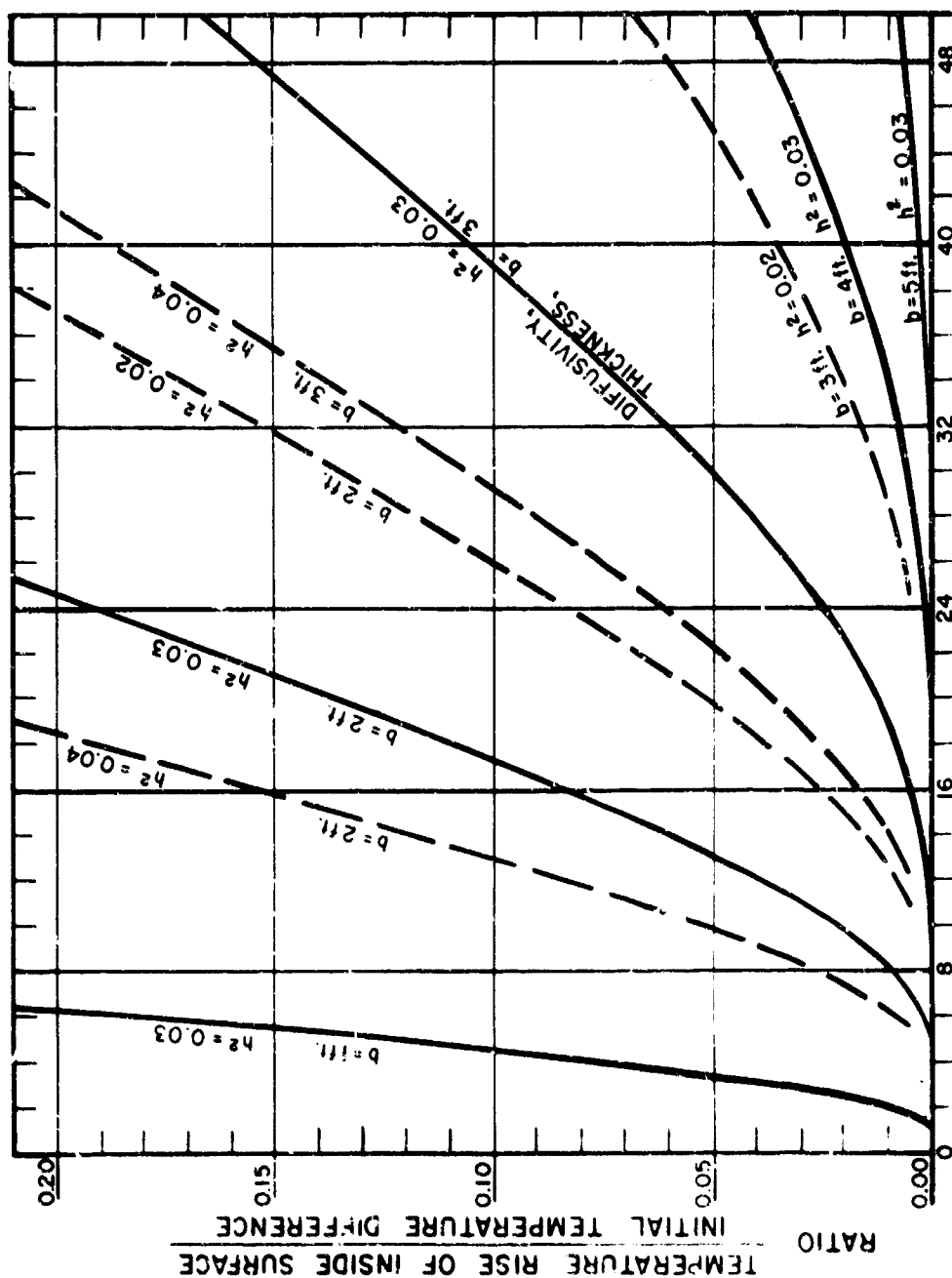
#### MECHANICAL SYSTEMS

If the evaluations in a cost-effectiveness study were assigned on the basis of economy, versatility and ability to perform satisfactorily under all operating conditions, the preferred environmental control system for shelters might well be one which includes the following features:

1. A recirculating air system with fan, distribution ductwork, diffusion outlets, mixing plenum and interconnections to supply air to occupied spaces without objectionable drafts.
2. A separate blower for the intake of minimum quantities of outside air as determined by requirements for oxygen replacement, carbon dioxide dilution, combustion, exhaust and pressurization.
3. Air cooling and dehumidifying apparatus using well water as a coolant with sufficient capacity to absorb internal heat loads and to avoid moisture condensation on shelter surfaces.
4. A simple and reliable sub-system for controlling and coordinating the operation of all equipment.

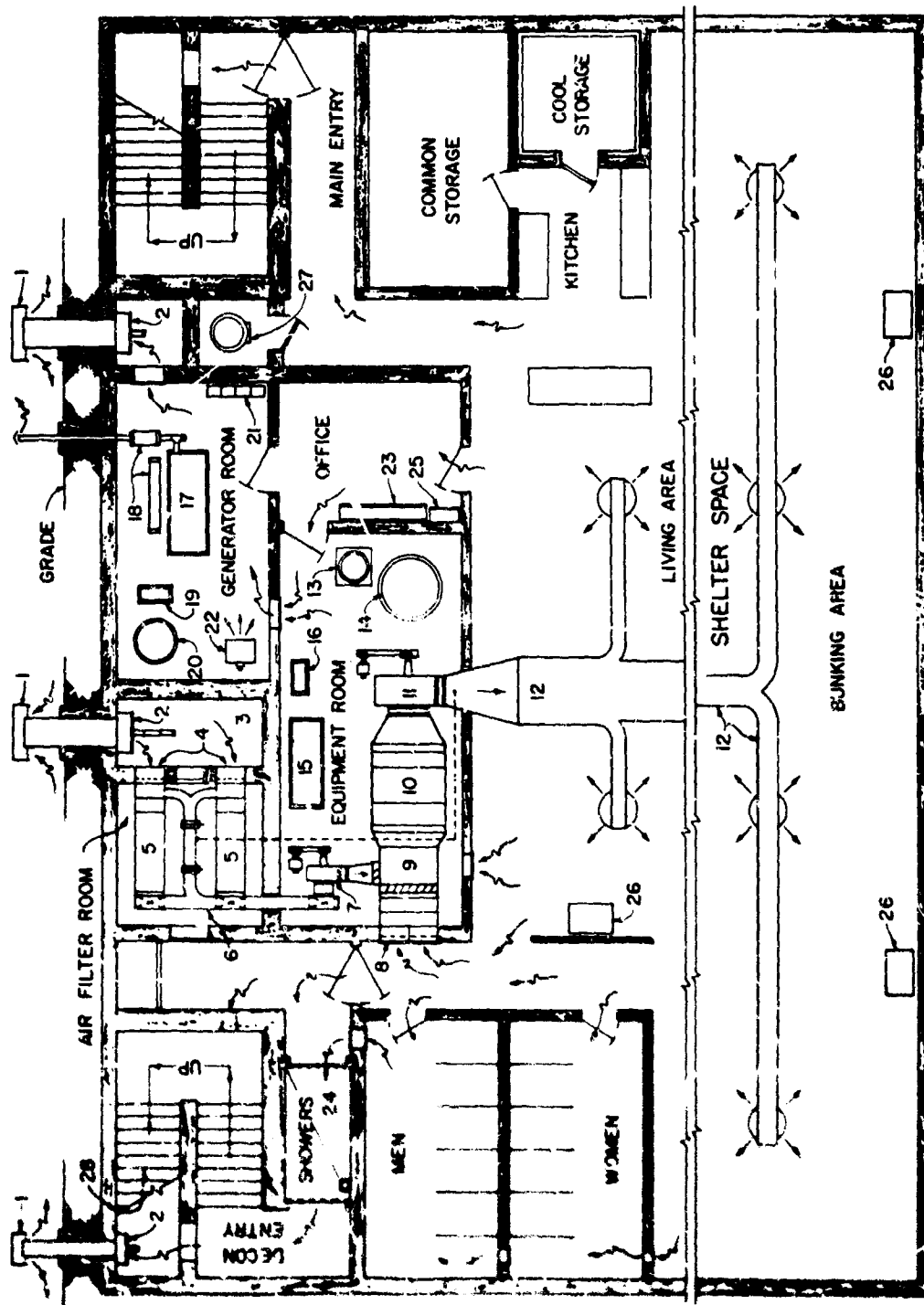
The configuration and flow diagram shown in Figure 12 is a rather extensive development of this concept, but is adaptable by omissions and minor rearrangement to the most fundamental requirements. By planning for possible improvements, future modifications can be facilitated, or an inferior final arrangement can be avoided. In the configuration shown in Figure 12, utility and service areas are grouped for ventilation in sequence by waste air leaving the shelter. The numbered items may be identified as follows:

1. Weatherproof hoods of the mushroom type for intake and exhaust air. If the air intake fixture is designed for a low entering air velocity (less than 200 ft/min), coarse particulates having a higher terminal velocity of fall would be separated by gravity from the fresh air supply.



TIME AFTER EXPOSURE OF OUTSIDE ROOF SURFACE  
TO FIRE TEMPERATURE (HOURS)  
TEMPERATURE RISE OF INSIDE SURFACE OF SHELTER ROOF MASS  
AFTER OUTSIDE SURFACE IS EXPOSED TO FIRE TEMPERATURE

FIG. 11



UNDERGROUND COMMUNITY SHELTER  
ENVIRONMENTAL CONTROL SYSTEM  
CONFIGURATION AND AIR FLOW DIAGRAM

FIG. 12

2. Automatic blast closures for protective structures having appreciable resistance to dynamic loading. Blast valves would be superfluous in fallout shelters having little inherent blast resistance.
3. Fresh air intake plenum or expansion chamber.
4. Fresh air filters or prefilters. For example, these may be panel filters with a dry or viscous-coated pleated media of fine bonded glass fibers supported in a metal frame by pleated wire screen on both sides.
5. Gas-particulate filters for protection against chemical and biological agents in shelters planned for this purpose.
6. Fresh air ductwork with bypass for the gas-particulate filters. The space between the two bypass valves or dampers is pressurized by a pipe connection to the main fan discharge to assure that any valve leakage is uncontaminated air.
7. Fresh air blower with electric motor drive. Since this blower pressurizes the space and must be capable of operating against a rather high system resistance if air flow is restricted by gas-particulate filters and blast valves, Class II construction may be indicated.
8. Grilled opening for recirculated air. Behind the grille are optional prefilters and activated-charcoal filters for odor control.
9. Mixing plenum with adjustable dampers for fresh and recirculated air.
10. Air conditioning chamber with cooling and heating coils. Cooling coils use well water and heating coils use waste heat from the engine-generator.
11. Main fan with electric motor drive.
12. Air distribution ductwork with diffusion outlets. If cooling and dehumidifying equipment is not provided, an air supply system which introduces all of the air at the end of the occupied space most remote from the exhaust openings would probably result in minimum discomfort during warm weather.
13. Well and pump for potable and cooling water. A charging well for waste water may be desirable. If well water is not available, other means must be substituted for cooling the shelter and equipment. Heat transfer apparatus for blast shelters should be blast resistant if installed outside a protective structure.

14. Hydropneumatic tank for pressure water system.
15. Optional package water chiller for alternative or supplementary use. This item may be required in hot humid climates when cool well water is not available.
16. Chilled-water circulating pump. This item may be an integral part of the package water chiller.
17. Emergency engine-generator set cooled by a heat exchanger or, alternatively, by a remote radiator. The fuel storage tank is not shown.
18. Heat exchanger and muffler for engine cooling and waste heat recovery.
19. Hot water circulating pump.
20. Hot water storage tank.
21. Batteries for starting engine and emergency lighting.
22. Recirculating unit cooler for generator room.
23. Control cabinet for functional control apparatus.
24. Decontamination facility for entry of contaminated personnel.
25. Cabinet for detection and test instruments.
26. Portable manually-operated life-support systems for a maximum of 24-hour sealed operation.
27. Incinerator for combustible waste materials.
28. Sewage sump and pump below stairs.

It should be emphasized that this illustrative system is not representative of minimum requirements. In a fallout shelter with a simple system for cooling by ventilation with outside air, many of the items would be omitted -- but the basic features of the ultimate plan could be retained. Every listed item of equipment has a function which could contribute materially in time of need to the health and safety of the people.



## CHAPTER 11

### DOSE AND DOSE RATE CALCULATIONS

Since the radiation intensity will decay with the passage of time, it is important to be able to compute problems of this nature to determine when and for what length of time it would be safe to emerge from a sheltered area. An indication of the manner in which the dose rate of the actual mixture of fallout fission products decreases with time may be obtained from the following approximate rule: for every seven-fold increase in time after the explosion, the dose rate decreases by a factor of ten. For example, if the radiation dose rate at 1 hour after the explosion is taken as a reference point, then 7 hours after the explosion the dose rate will have decreased to one-tenth; at  $7 \times 7 = 49$  hours after the explosion it will be one hundredth of that at 1 hour after the burst. The dose rate is usually expressed in "roentgens per hour" and the total dose is usually expressed in "roentgens". A more accurate method for determining dose rate and total dose can be obtained by use of the following expressions:

#### Dose Rate Formula

$$R_1 = R T^n$$

Where

$R_1$  = Dose Rate one hour after detonation (H+1)

$R$  = Dose Rate at time  $T$

$T$  = Time (hours) after detonation

$n = 1.2$

#### Dose Formula

$$D = \frac{R_1}{n-1} (T_1^{1-n} - T_2^{1-n})$$

Where

$D$  = Dose from time  $T_1$  to  $T_2$

$R_1$  = Dose Rate one hour after detonation (H+1)

$T_1$  = Time of entry

$T_2$  = Time of exit

$n = 1.2$

T = Time in hours	$t^{1.2}$	$t^{-0.2}$
0.1	0.0631	1.586
0.2	0.1450	1.381
0.3	0.2358	1.273
0.4	0.3330	1.202
0.5	0.4352	1.149
0.6	0.5417	1.110
0.7	0.6518	1.074
0.8	0.7651	1.046
0.9	0.8812	1.021
1.0	1.000	1.000
1.5	1.627	0.922
2.0	2.300	0.871
2.5	3.003	0.833
3.0	3.737	0.803
4.0	5.278	0.758
5.0	6.899	0.725
6.0	8.586	0.698
7.0	10.33	0.678
8.0	12.13	0.660
9.0	13.96	0.644
10.0	15.85	0.631
11.0	17.77	0.619
12.0	19.73	0.608
13.0	21.71	0.599
14.0	23.74	0.590
15.0	25.78	0.582
16.0	27.86	0.574
17.0	29.96	0.567
18.0	32.09	0.560
19.0	34.23	0.555
20.0	36.41	0.550
21.0	38.61	0.544
22.0	40.82	0.539
23.0	43.06	0.534
24.0	45.31	0.530
25.0	47.59	0.525
26.0	49.89	0.521
27.0	52.20	0.518
28.0	54.52	0.514
29.0	56.87	0.510
30.0	59.23	0.506
31.0	61.61	0.503
32.0	64.00	0.500

33.0	66.41	0.497
34.0	68.83	0.494
35.0	71.27	0.491
36.0	73.72	0.488
37.0	76.18	0.486
38.0	78.66	0.483
39.0	81.15	0.480
40.0	83.67	0.478
41.0	86.17	0.476
42.0	88.70	0.474
43.0	91.23	0.472
44.0	93.79	0.470
45.0	96.35	0.467
46.0	98.93	0.465
47.0	101.5	0.463
48.0	104.1	0.461
49.0	106.7	0.459
50.0	109.3	0.457
55.0	122.6	0.449
60.0	136.1	0.441
65.0	149.8	0.434
70.0	163.7	0.427
72.0	169.4	0.425
75.0	177.8	0.422
80.0	192.2	0.417
85.0	206.7	0.412
90.0	211.1	0.407
95.0	236.2	0.402
96.0	239.2	0.401
100.0	251.2	0.398
120.0	312.6	0.384
140.0	376.2	0.372
144.0	389.1	0.370
160.0	442.5	0.362
168.0 (1 wk)	468.1	0.360
180.0	508.5	0.354
220.0	577.1	0.347
250.0	754.3	0.332
300.0	938.7	0.319
336.0 (2 wk)	1075.0	0.313
504.0 (3 wk)	1745.0	0.288
672.0 (4 wk)	2471.0	0.272
720.0 (1 Mo.)	2611.0	0.268
1440.0 (2 Mo.)	6166.0	0.234
2160.0 (3 Mo.)	10031.0	0.216

## SAMPLE DOSE AND DOSE RATE PROBLEMS

### Formula Method

#### Dose Rate Problem

If the dose rate at a given location one hour after detonation was 30 r/hr, what would the dose rate be at this location 12 hours after detonation?

#### Solution

$$R_1 = R T^n$$

$$R_1 = 30 \text{ r/hr}$$

Substitute values in the above formula.

$$R = ?$$

$$30 = R (12)^{1.2}$$

$$T = 12 \text{ hours}$$

$$\text{From page 2: } (12)^{1.2} = 19.73$$

$$n = 1.2$$

$$\text{Therefore: } 30 = R (19.73)$$

$$R = \frac{30}{19.73} = 1.52 \text{ r/hr}$$

#### Dose Problem

What dose would a civil defense monitoring team receive in a radioactive contaminated area if the team entered the area 5 hours after a nuclear burst and stayed for a period of 10 hours? The dose rate at H+1 was 50 r/hr.

#### Solution

$$D = \frac{R_1}{n-1} (T_1^{1-n} - T_2^{1-n})$$

$$D = ?$$

Substitute values in the above formula.

$$R_1 = 50 \text{ r/hr}$$

$$D = \frac{50}{1.2-1} (5^{1-1.2} - 15^{1-1.2})$$

$$T_1 = 5 \text{ hours}$$

$$D = \frac{50}{.2} (5^{-0.2} - 15^{-0.2})$$

$$T_2 = 5 + 10 = 15 \text{ hours}$$

From page 2:

$$n = 1.2$$

$$5^{-0.2} = 0.725 \text{ and } 15^{-0.2} = 0.582$$

$$\text{Therefore: } D = 250 (0.725 - 0.582)$$

$$D = (250) (0.143)$$

$$D = 36 \text{ r}$$

## SAMPLE DOSE AND DOSE RATE PROBLEMS

### Rule of Thumb Method

#### Dose Rate

FOR A SEVEN-FOLD INCREASE IN TIME THERE IS A TEN-FOLD DECREASE IN THE DOSE RATE. (7:10 rule)

#### Examples:

$$R_1 = 100 \text{ r/hr}$$

$$R_{49} = 1 \text{ r/hr}$$

$$R_7 = 10 \text{ r/hr}$$

$$R_{343} = 0.1 \text{ r/hr}$$

and

$$R_5 = 57 \text{ r/hr}$$

$$R_{245} = 0.57 \text{ r/hr}$$

$$R_{35} = 5.7 \text{ r/hr}$$

#### Dose

$$D_{\infty} = 5 RT$$

where

$D_{\infty}$  = dose to infinity.

$R$  = dose rate as measured by instrument.

$T$  = time in hours after detonation at which measured dose rate was read.

#### Example:

If the dose rate at H+7 is 45 r/hr, what would be the dose to infinity?

#### Solution:

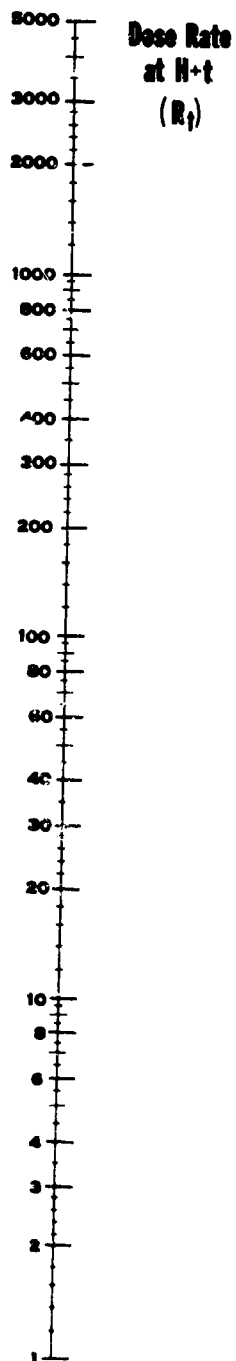
$$D_{\infty} = 5 RT = 5(45 \text{ r/hr})(7 \text{ hr}) = 1575 \text{ r}$$

#### Example:

If the dose rate in an area is 100 r/hr at H+5 and 42 r/hr at H+10, what would be the dose from H+5 to H+10?

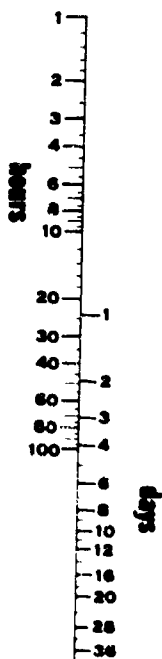
#### Solution:

$$\begin{aligned} D &= \text{Dose to infinity (H+5)} - \text{Dose to infinity (H+10)} \\ D &= 5(100 \text{ r/hr})(5 \text{ hr}) - 5(42 \text{ r/hr})(10 \text{ hr}) \\ D &= 2500 \text{ r} - 2100 \text{ r} = 400 \text{ r} \end{aligned}$$

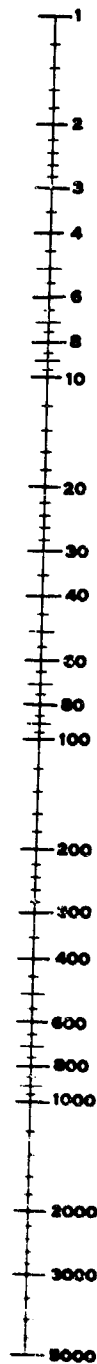


# DOSE RATE NOMOGRAM

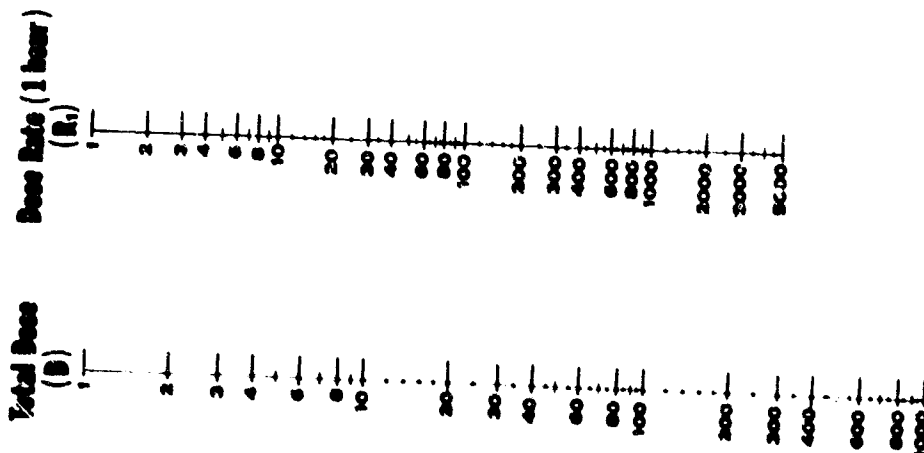
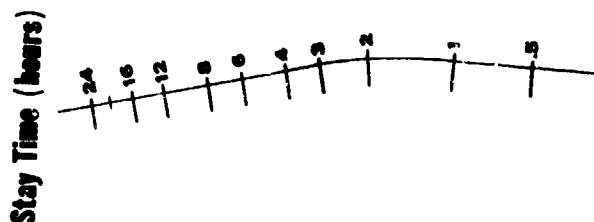
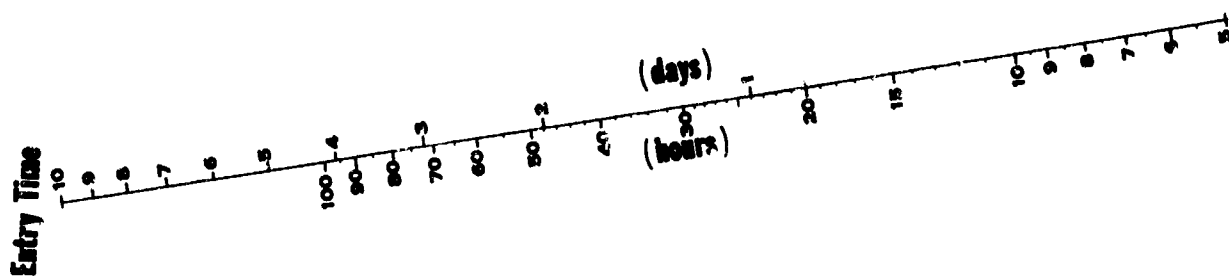
**Time After Burst**



**Dose Rate  
at H+1  
(R<sub>1</sub>)**



# ENTRY TIME - STAY TIME TOTAL DOSE NOMOGRAM



## SAMPLE DOSE RATE - DOSE - ENTRY TIME - STAY TIME PROBLEMS

### Dose Rate Nomogram Method

To use the Dose Rate Nomogram connect any two known quantities with a straightedge and read the unknown quantity directly.

**Example:** If the dose rate in an area is 60 r/hr at H+5, what will be the dose rate at H+10?

**Solution:** With a straightedge, connect 60 r/hr on the "Dose Rate at H+t" column with 5 hours on the "Time After Burst" column. The dose rate of 410 r/hr is read on the "Dose Rate at H+1" column. Next, connect, with the straightedge, 10 hours on the "Time After Burst" column with 410 r/hr on the "Dose Rate at H+1" column and read the answer directly from the "Dose Rate at H+t" column.

**Answer:** 26 r/hr.

### ENTRY TIME - STAY TIME - TOTAL DOSE NOMOGRAM METHOD

To use this nomogram connect two known quantities with a straightedge and locate the point on the "D/R" column where the straightedge crosses it. Connect this point with a third known quantity and read the answer from the appropriate column.

**Dose** - Find the total exposure dose for an individual who must work in an area in which the dose rate was 300 r/hr at H+1. Entry will be made at H+11 and the length of stay will be 4 hours.

**Solution:** Connect H+11 on the "Entry Time" column with 4 hours on the "Stay Time" column and read 0.19 from the "D/R<sub>1</sub>" column and 300 r/hr on the "Dose Rate at H+1" column. Finally, read the answer on the "Total Dose" column.

**Answer:** 60 r.

**Stay Time** - Entry into an area with a dose rate of 100 r/hr at H+1 will be made at H+6. What will be the maximum mission stay time, if the exposure dose is not to exceed 20 r?

**Solution:** Connect 20 r in the "Total Dose" column with 100 r/hr in the "Dose Rate at H+1" column and read 0.2 in the "D/R<sub>1</sub>" column. Connect 0.2 in the "D/R<sub>1</sub>" column with 6 hours in the "Entry Time" column, and read the answer directly from the "Stay Time" column.

**Answer:** 2.1 hours.

**Entry Time** - The dose rate in an area at H+7 is 35 r/hr. The stay time is to be 5 hours and the mission dose is set at 35 r. What is the earliest possible entry time?



**Solution:** Find the dose rate at H+1 from the Dose Rate Nomogram. Connect this value on the "Dose Rate at H+1" column with 35 r on the "Total Dose" column and read 0.1 on the "D/R<sub>1</sub>" column. Connect 0.1 on the "D/R<sub>1</sub>" column with 5 hours on the "Stay Time" column and read the answer from the "Entry Time" column.

**Answer:** H+24.

#### DOSE RATE PROBLEMS

1. If the dose rate at one hour after burst is 40 r/hr, what will be the dose rate at 2, 4, 6, 8, and 10 hours?
2. If the dose rate at H+1 is 100 r/hr, what will be the dose rate at 2, 4, and 10 hours?
3. If the dose rate at H+1 is 350 r/hr, what will be the dose rate at 5, 8, and 12 hours?
4. If the dose rate at H+6 was 45 r/hr, what would be the dose rate at 1, 9, 12, and 15 hours?
5. If the dose rate at H+12 was 80 r/hr, what would be the dose rate at 1, 8, and 24 hours?
6. If the dose rate at H+20 was 10 r/hr, what would be the dose rate at 1, 20, 25, and 32 hours?
7. If the dose rate at H+30 is 10 r/hr, when would the dose rate be 7 r/hr?
8. At H+20 days the dose rate in an area is 3 r/hr. What will be the dose rate at H+25 days?
9. In a sheltered area with a protection factor of 100, the dose rate is 10 r/hr at H+10. What was the unsheltered dose rate at H+18?
10. In a shelter with a protection factor of 1,000, the dose rate at H+24 is 15 r/hr. What will be the dose rate in the shelter at H+40?

#### DOSE PROBLEMS

11. If the dose rate at H+1 was 200 r/hr, what would be the dose of a monitor if he entered the area at H+12 and stayed 4 hours?
12. If the dose rate at H+1 was 50 r/hr, what would be the dose of a monitor if he stayed in this area from H+5 to H+8?

13. If the dose rate at H+1 was 500 r/hr, what would be the total dose of a monitor who remained in this area for a 1.5 hour period beginning at H+12?
14. What would be a monitor's dose if he entered an area at H+6 and left at H+8? At the time of entry the dose rate was 15 r/hr.
15. Firemen must put out a fire in an area where the dose rate was 50 r/hr at H+7. What will be their mission dose if it takes 6 hours to fight the fire and they start their mission at H+12?
16. Vital medical supplies must be moved to a shelter area. The task will require 30 minutes. If the worker enters the area at H+6 when the dose rate is 200 r/hr, what dose will he receive?
17. An individual left a shelter at H+6 on a mission to a nearby shelter but never arrived at the other shelter. At H+30 a rescue team found him unconscious in the contaminated area outside the original shelter. At that time the dose rate was 14 r/hr. What dose was received by the unconscious individual?
18. A rescue team entered a contaminated area at H+12 and accomplished a task in 4 hours. What was their dose if the dose rate at time of exit was 12 r/hr?
19. No water is available in a shelter. There is a safe supply nearby. It is a 45 minute walk to the water and the mission will begin at H+10. If the dose rate at H+7 was 30 r/hr, what dose will be received in obtaining the water for the shelter?
20. What is the dose received in a shelter from H+18 to H+24, if the unsheltered dose rate at H+16 is 120 r/hr and the shelter protection factor is 200?

#### STAY TIME PROBLEMS

21. A mission dose is set at 25 r and the mission will begin at H+12. What stay time is permitted, if the dose rate at H+1 was 500 r/hr?
22. At H+1 the dose rate was 200 r/hr. If entry into the area is made at H+6 and the mission dose is set at 50 r, what is the allowable stay time?
23. A family entered a contaminated area at H+5. Their dose should not exceed 35 r. How long can they stay in this area if the dose rate at time of entry was 20 r/hr?
24. At H+12 a monitor must start an emergency mission outside his assigned shelter. At H+6 the outside dose rate was 75 r/hr. If his mission dose is not to exceed 20 r, how long can he take for the task?

25. At H+3 the dose rate in an area was 40 r/hr. A rescue squad entered the area at H+5. How long can they stay in the area if their dose is not to exceed 25 r?
26. Personnel working in a warehouse in a contaminated area received a dose of 150 r. At H+1 the dose rate was 1,300 r/hr and they entered the working area at H+8. How long were they in the area?
27. A message must be hand carried to another shelter. What is the maximum time for the mission if the average dose rate between the shelters was 90 r/hr at H+2? The mission dose is set at 35 r and the messenger is to leave shelter at H+6.
28. At H+15 a Radar Officer must move to another control station 75 miles away. The average dose rate over the area of travel was 75 r/hr at H+6. How fast will he have to travel in order not to exceed a dose of 50 r?
29. An individual travels at a speed of 35 mph through a contaminated area where the average dose rate was 100 r/hr at H+5. How far will he be able to travel before seeking shelter if he entered the area at H+13 and must limit his dose to 80 r?

#### ENTRY TIME PROBLEMS

31. If the dose rate in an area was 300 r/hr at H+1, when can a monitor enter the area for a 3 hour stay and receive less than 50 r?
32. A monitor must stay in an area for 1 hour. The dose rate in this area at H+1 was 150 r/hr. He must limit his dose to 15 r. When can he enter?
33. In order to keep a monitor's dose below 20 r for a stay time of 2 hours, what is the earliest possible entry time into an area where the dose rate was 120 r/hr at H+1?
34. If the dose rate in an area is 5 r/hr at H+20 and an individual must stay there 3 hours, what is the earliest time he can enter and not exceed a dose of 10 r?
35. A mission dose is set at 35 r. The dose rate in the area was 18 r/hr at H+15. When can workers enter this area for a 3 hour period?

36. The task of removing valuable equipment which is located in a contaminated area will require 3 hours. The mission dose is set at 50 r and the dose rate at H+9 was 50 r/hr. When can the salvage crew enter the area?
37. A monitor must make a survey of an area which will require 2 hours. The mission dose is set at 35 r and the dose rate in the area was 18 r/hr at H+1 days. When will the monitor be able to enter the area?
38. People want to move from an improvised shelter to a community shelter. At H+6 the route to be traveled had an average dose rate of 85 r/hr. The trip will take 2 hours and the mission dose is 50 r. When can they leave?
39. A supply of drugs must be delivered as soon as possible to a shelter. The drive takes 3 hours. The average dose rate along the route to be followed was 125 r/hr at H+4. The mission dose is 75 r. What is the earliest time that the drugs can arrive at the shelter?
40. A shelter with a protection factor of 500 is running low on food. The nearest supply would require 1 hour travel round trip to obtain it. The average dose rate over the route to be traveled was 60 r/hr at H+7. The mission dose is set at 50 r. When can the mission be started to obtain the food?

NOTES

Answers to Dose and Dose Rate Problems

1. 18 r/hr, 7.6 r/hr, 4.7 r/hr,  
3.4 r/hr, 2.6 r/hr
2. 44 r/hr, 19 r/hr, 6.5 r/hr
3. 51 r/hr, 30 r/hr, 15 r/hr
4. 380 r/hr, 28 r/hr, 20 r/hr,  
15 r/hr
5. 1,600 r/hr, 58 r/hr, 35 r/hr
6. 370 r/hr, 10 r/hr, 8 r/hr,  
6 r/hr
7. H+40
8. 2.6 r/hr
9. 500 r/hr
10. 8 r/hr
11. 35 r
12. 15 r
13. 36 r
14. 25 r
15. 120 r
16. 90 r
17. 800 r
18. 60 r
19. 27 r
20. 2.7 r
21. 1 hour
22. 2.7 hours
23. 2.2 hours
24. .6 hour
25. 1.5 hours
26. 1.6 hours
27. 1.8 hours
28. 38 mph
29. 95 miles
31. H+11
32. H+6
33. H+7
34. H+27
35. H+21
36. H+22
37. H+23
38. H+17
39. H+18
40. H+8